EXHIBIT 16

Central Files

PROPRIETARY INFORMATION

For Authorized Company Use Only

EXXON RESEARCH AND ENGINEERING COMPANY

P.O. BOX 101, FLORHAM PARK, NEW JERSEY 07932

EXXON ENGINEERING PETROLEUM DEPARTMENT
Planning Engineering Division

Cable: ENGREXXON, N.Y.

R. L. MASTRACCHIO
Manager
L. E. Hill
Senior Eng. Assoc.

October 16, 1979

Controlling Atmospheric CO_2

79PE 554

Dr. R. L. Hirsch:

The attached memorandum presents the results of a study on the potential impact of fossil fuel combustion on the CO_2 concentration in the atmosphere. This study was made by Steve Knisely, a summer employee in Planning Engineering Division.

The study considers the changes in future energy sources which would be necessary to control the atmospheric CO_2 concentration at different levels. The principle assumption for the CO_2 balance is that 50% of the CO_2 generated by fossil fuels remains in the atmosphere. This corresponds to the recent data on the increasing CO_2 concentration in the atmosphere compared to the quantity of fossil fuel combusted.

Present climatic models predict that the present trend of fossil fuel use will lead to dramatic climatic changes within the next 75 years. However, it is not obvious whether these changes would be all bad or all good. The major conclusion from this report is that, should it be deemed necessary to maintain atmospheric CO_2 levels to prevent significant climatic changes, dramatic changes in patterns of energy use would be required. World fossil fuel resources other than oil and gas could never be used to an appreciable extent.

No practical means of recovering and disposing of CO_2 emissions has yet been developed and the above conclusion assumes that recovery will not be feasible.

It must be realized that there is great uncertainty in the existing climatic models because of a poor understanding of the atmospheric/terrestrial/oceanic CO_2 balance. Much more study and research in this area is required before major changes in energy type usage could be recommended.

W. L. Ferrall
W. L. FERRALL

WLF:ceg
Attachment

c: J. F. Black
J. W. Herrmann
L. E. Hill
E. D. Hooper
F. J. Kaiser
R. L. Mastracchio
W. H. Mueller
H. Shaw
G. O. Wilhelm

CONTROLLING THE CO_2 CONCENTRATION IN THE ATMOSPHERE

The CO_2 concentration in the atmosphere has increased since the beginning of the world industrialization. It is now 15% greater than it was in 1850 and the rate of CO_2 release from anthropogenic sources appears to be doubling every 15 years. The most widely held theory is that:

- The increase is due to fossil fuel combustion
- Increasing CO_2 concentration will cause a warming of the earth's surface
- The present trend of fossil fuel consumption will cause dramatic environmental effects before the year 2050.

However, the quantitative effect is very speculative because the data base supporting it is weak. The CO_2 balance between the atmosphere, the biosphere and the oceans is very ill-defined. Also, the overall effect of increasing atmospheric CO_2 concentration on the world environment is not well understood. Finally, the relative effect of other impacts on the earth's climate, such as solar activity, volcanic action, etc. may be as great as that of CO_2.

Nevertheless, recognizing the uncertainty, there is a possibility that an atmospheric CO_2 buildup will cause adverse environmental effects in enough areas of the world to consider limiting the future use of fossil fuels as major energy sources. This report illustrates the possible future limits on fossil fuel use by examining different energy scenarios with varying rates of CO_2 emissions. Comparison of the different energy scenarios show the magnitude of the switch from fossil fuels to non-fossil fuels that might be necessary in the future. Non-fossil fuels include fission/fusion, geothermal, biomass, hydroelectric and solar power. The possible environmental changes associated with each scenario are also discussed.

CONCLUSIONS

As stated previously, predictions of the precise consequences of uncontrolled fossil fuel use cannot be made due to all of the uncertainties associated with the future energy demand and the global CO_2 balance. On the basis that CO_2 emissions must be controlled, this study examined the possible future fuel consumptions to achieve various degrees of control. Following are some observations and the principle conclusions from the study:

- The present trends of fossil fuel combustion with a coal emphasis will lead to dramatic world climate changes within the next 75 years, according to many present climatic models.

- The CO_2 buildup in the atmosphere is a worldwide problem. U.S. efforts to restrict CO_2 emission would delay for a short time but not solve the problem.

- Warming trends which would move the temperate climate northward may be beneficial for some nations (i.e., the USSR, see Figure 1) and detrimental for others. Therefore, global cooperation may be difficult to achieve.

- Removal of CO_2 from flue gases does not appear practical due to economics and lack of reasonable disposal methods.

- If it becomes necessary to limit future CO_2 emissions without practical removal/disposal methods, coal and possibly other fossil fuel resources could not be utilized to an appreciable extent.

- Even with dramatic changes in current energy resource use, it appears unlikely that an increase of 50% over the pre-industrial CO_2 level can be avoided in the next century. This would be likely to cause a slight increase in global temperatures but not a significant change in climate, ocean water level or other serious environmental efforts.

The potential problem is great and urgent. Too little is known at this time to recommend a major U.S. or worldwide change in energy type usage but it is very clear that immediate research is necessary to better model the atmosphere/terrestrial/oceanic CO_2 balance. Only with a better understanding of the balance will we know if a problem truly exists.

Existing Data and Present Models

Since the beginning of industrialization, the atmospheric carbon dioxide concentration has increased from approximately 290 ppm in 1860 to 336 ppm today. Atmospheric CO_2 concentrations have been recorded on a monthly basis by C. D. Keeling since 1958 at Mauna Loa Observatory in Hawaii (see Figure 2). Seasonal variations are clearly shown with the CO_2 concentrations lowest during the North American and Eurasian summers, due to increased photosynthetic activities. Over the last ten years, the atmospheric concentration has been increasing at an average rate of about 1.2 ppm/year.

The present consumption of fossil fuels releases more than 5 billion tons of carbon as CO_2 into the atmosphere each year. Data to date indicate that of the amount released approximately one-half is absorbed by the oceans. The other half remains in the atmosphere. There is some question as to whether the terrestrial biosphere is a sink, absorbing atmospheric CO_2, or a source of CO_2 emissions, due to man's land clearing activities. Current opinion attributes the atmospheric CO_2 increase to fossil fuels and considers the biosphere input to be negligible.

Figure 3 shows the carbon cycle with the ocean and the biosphere as sinks for approximately 50% of the fossil fuel emissions. Most models show the ocean to be a major sink while the biosphere appears to be a much smaller sink if it absorbs any CO_2 at all. It is clear from Figure 3 that the net atmospheric increase in CO_2 is quite small compared to the quantities of CO_2 exchanged between the atmosphere and the earth. This makes it very difficult to analyze the fossil fuel impact on the overall carbon cycle.

The fossil fuel resource is very large compared to the quantity of carbon in the atmosphere. Therefore, if one half of the CO_2 released by combustion of fossil fuels remains in the atmosphere, only about 20% of the recoverable fossil fuel could be used before doubling the atmospheric CO_2 content.

The concern over the increasing CO_2 levels arises because of the radiative properties of the gas in the atmosphere. CO_2 does not affect the incoming short-wave (solar) radiation to the earth but it does absorb long-wave energy reradiated from the earth. The absorption of long-wave energy by CO_2 leads to a warming of the atmosphere. This warming phenomenom is known as the "greenhouse effect."

A vast amount of speculation has been made on how increased CO_2 levels will affect atmospheric temperatures. Many models today predict that doubling the 1860 atmospheric CO_2 concentration will cause a 1^o to 5^oC global temperature increase (see Figure 4). Extrapolation of present fossil fuel trends would predict this doubling of the CO_2 concentration to occur about 2050. A temperature difference of 5^oC is equal to the difference between a glacial and an interglacial period. The temperature increases will also tend to vary with location being much higher in the polar region (see Figure 5). These temperature predictions may turn out too high or low by several fold as a result of many feedback mechanisms that may arise due to increased temperatures and have not been properly accounted for in present models.

These mechanisms include:

- A decrease in average snow and ice coverage. This is a positive feedback mechanism since it would result in a decrease of the earth's albedo (reflectivity) which would produce an added warming effect.

- Cloud Cover. This is considered the most important feedback mechanism not accounted for in present models. A change of a few percent in cloud cover could cause larger temperature changes than those caused by CO_2. Increased atmospheric temperature could cause increased evaporation from the oceans and increased cloud cover.

- Ocean and Biosphere Responses. As the CO_2 level is increased and the ambient temperature rises, the ocean may lose some of its capacity to absorb CO_2 resulting in a positive feedback. However, increased CO_2 levels could increase photosynthetic activities which would then be a negative feedback mechanism.

As evidenced by the balance shown in Figure 3, the atmospheric carbon exchange with the terrestrial biosphere and the oceans is so large that small changes due to these feedback mechanisms could drastically offset or add to the impact of fossil fuel combustion on the earth's temperature.

Appendix A gives one, but not unanimous, viewpoint of how the environment might change if the feedback mechanisms are ignored. The contribution that will ultimately be made by these feedback mechanisms is unknown at present.

Energy Scenarios for Various CO_2 Limits

Using the CO_2 atmospheric concentration data recorded to date, the correlation of these data with fossil fuel consumption and the proposed "greenhouse effect" models, this study reviews various world energy consumption scenarios to limit CO_2 atmospheric buildup. The concentration of CO_2 in the atmosphere is controlled in these studies by regulating the quantity of each type of fossil fuel used and by using non-fossil energy sources when required. The quantity of CO_2 emitted by various fuels is shown in Table 1. These factors were calculated based on the combustion energy/carbon content ratio of the fuel and the thermal efficiency of the overall conversion process where applicable. They show the high CO_2/energy ratio for coal and shale and the very high ratios for synthetic fuels from these base fossil fuels which are proposed as fuels of the future.

The total world energy demand used in these scenarios is based upon the predictions in the Exxon Fall 1977 World Energy Outlook for the high oil price case for the years 1976 to 1990. It is assumed that no changes in the sources of supply of energy could be made during this period of time. Case A, which has no restrictions on CO_2 emissions, follows the high oil price predictions until 2000.

Petroleum production and consumption is the same in each scenario. The high oil price case predictions are followed until 2000. After 2000 petroleum production continues to increase until a reserve to production ratio (R/P) equals ten to one. Production peaks at this point and then continues at a ten to one R/P ratio until supplies run out.

The consumption of coal, natural gas and non-fossil fuels (fission/fusion, geothermal, biomass, hydroelectric and solar power) vary with each scenario. Shale oil makes small contributions past the year 2000. It is not predicted to be a major future energy source due to environmental damage associated with the mining of shale oil, and also due to rather large amounts of CO_2 emitted per unit energy generated (see Table 1). If more shale oil were used, it would have the same effect on CO_2 emissions as the use of more coal. The fossil fuel resources assumed to be recoverable are tabulated in Appendix B.

A. No Limit on CO_2 Emissions

In this scenario no limitations are placed upon future fossil fuel use. The use of coal is emphasized for the rest of this century and continues on into the next century. The development and use of non-fossil fuels continue to grow but without added emphasis. Natural gas production continues at a slowly increasing rate until an R/P ratio of 7/1 is reached around 2030. Production after 2030 continues at a 7/1 ratio until reserves run out. Figure 6 shows the future energy demand for this scenario.

Figure 7 shows that the CO_2 buildup from this energy strategy is quite rapid. The yearly atmospheric CO_2 increase rises from 1.3 ppm in 1976 to 4.5 ppm in 2040. Noticeable temperature changes would occur around 2010 as the concentration reaches 400 ppm. Significant climatic changes occur around 2035 when the concentration approaches 500 ppm. A doubling of the pre-industrial concentration occurs around 2050. The doubling would bring about dramatic changes in the world's environment (see Appendix A). Continued use of coal as a major energy source past the year 2050 would further increase the atmospheric CO_2 level resulting in increased global temperatures and environmental upsets.

B. CO_2 Increase Limited to 510 ppm

This energy scenario is limited to a 75% increase over the pre-industrial concentration of 290 ppm. No limitations are placed on petroleum production. Natural gas production is encouraged beginning in 1990 to minimize coal combustion until non-fossil fuels are developed. Production of natural gas would increase until 2010 when an R/P ratio of 7/1 would be reached. Production would then continue at a R/P of 7/1 until supplies ran out. The development and use of nonfossil fuels are emphasized beginning the 1990's. Non-fossil fuels start to be substituted for coal in 1990's. Figure 8 shows the future energy demand by fuel for this scenario.

Figure 9 shows the atmospheric CO_2 concentration trends for this scenario. The lower graph shows the maximum yearly atmospheric CO_2 increase allowable for the 510 ppm limit. The yearly CO_2 increase peaks in 2005 when it amounts to 2.3 ppm and then steadily decreases reaching 0.2 ppm in 2100. A 0.2 ppm increment is equivalent to the direct combustion of 5.1 billion B.O.E. of coal. This would be approximately 2 to 3% of the total world energy demanded in 2100. (For more detail on the construction of Figure 9, see Appendix C.)

A comparison of the Exxon year 2000 predictions and this scenario's year 2000 requirements shows the magnitude of possible future energy source changes. The Exxon predictions call for nonfossil fuels to account for 18 billion B.O.E. in 2000. This scenario requires that 20 billion B.O.E. be supplied by non-fossil fuels by

2000. This difference of 2 billion B.O.E. is equivalent to the power supplied by 214-1000 MW nuclear power plants operating at 60% of capacity. If it were supplied by methane produced from biomass, it would be equivalent to 80,000 square miles of biomass at a yield of 50 ton/acre, heat value of 6500 Btu/dry pound and a 35% conversion efficiency to methane. Therefore even a 20% increase in non-fossil fuel use is a gigantic undertaking.

The magnitude of the change to non-fossil fuels as major energy sources is more apparent when scenarios A and B are compared in the year 2025. Scenario B requires an 85 billion B.O.E. input from non-fossil fuels in 2025. This is almost double the 45 billion B.O.E. input predicted in scenario A. This 35 billion B.O.E. difference is approximately equal to the total energy consumption for the entire world in 1970.

The environmental changes associated with this scenario wouldn't be as severe as if the CO_2 concentration were allowed to double as in scenario A. Noticeable temperature changes would occur around 2010 when the CO_2 concentration reaches 400 ppm. Significant climate changes would occur as the atmospheric concentration nears 500 ppm around 2080. Even though changes in the environment due to increased atmospheric CO concentrations are uncertain, an increase to 500 ppm would probably bring about undesirable climatic changes to many parts of the earth although other areas may be benefitted by the changes. (See Appendix A, part 1).

C. CO_2 Increase Limited to 440 ppm

This scenario limits future atmospheric CO_2 increases to a 50% increase over the pre-industrial concentration of 290 ppm. As in the previous case, no limitations are placed on petroleum production and increased natural gas production is encouraged. Much emphasis is placed on the development and use of non-fossil fuels. Non-fossil fuels are substituted for coal beginning in the 1990's. By 2010 they will have to account for 50% of the energy supplied worldwide. This would be an extremely difficult and costly effort if possible. In this scenario coal or shale will never become a major energy source. Figure 10 shows the future world energy demand by fuel for this scenario.

The atmospheric CO_2 concentration trends for this scenario are shown in Figure 11. To satisfy the limits of this scenario the yearly CO_2 emissions would have to peak in 1995 at 2.0 ppm,

and then rapidly decrease reaching a value of 0.04 ppm in 2100. A 0.04 ppm maximum allowable increase means that unless removal/disposal methods for CO_2 emissions are available only one billion B.O.E. of coal may be directly combusted in 2100 (or 1.4 billion Barrels of Oil). This would be less than 1% of the total energy demanded by the world in 2100.

To adhere to the 440 ppm limit, non-fossil fuels will have to account for 28 billion B.O.E. in 2000 as compared to 20 billion B.O.E. in scenario B and 18 billion B.O.E. in scenario A. This difference between scenarios A and C of 10 billion B.O.E. is equivalent to over 1000, 1000 MW nuclear power plants operating at 60% of capacity. Ten billion B.O.E. is also approximately equivalent to 400,000 square miles of biomass at 35% conversion efficiency to methane. This is equivalent to almost one-half the total U.S. forest land.

By 2025 the 110 billion B.O.E. input from non-fossil fuels called for in this scenario is more than twice as much as the 45 billion B.O.E. input predicted in scenario A. This difference of 65 billion is approximately equal to the amount of energy the entire world will consume in 1980. In terms of power plants, 65 billion B.O.E. is equivalent to almost 7000, 1000 MW nuclear power plants operating at 60% of capacity.

An atmospheric CO_2 concentration of 440 ppm is assumed to be a relatively safe level for the environment. A slight global warming trend should be noticeable but not so extreme as to cause major changes. Slight changes in precipitation might also be noticeable as the atmospheric CO_2 concentration nears 400 ppm.

S. KNISELY

REFERENCES

Corporate Planning Department, Exxon Corp. (Fall, 1977). World Energy Outlook, 1977-1990.

Flower, A. R. (1978). "World Oil Production," Scientific American 238 (3), pp. 42-49.

Griffith, E. D. and Clarke, A. W. (1979). "World Coal Production," Scientific American 240 (1), pp. 38-47.

McCormick, W. T., R. B. Kalisch, and T. J. Wander (1978). "AGA Study Assesses World Natural Gas Supply," The Oil and Gas Journal. February 13, 1978, pp. 103-106.

Peterson, E. K. (1969). "Carbon Dioxide Affects Global Ecology," Environmental Science and Technology 3 (11), pp. 1162-1169.

Rotty, R. M. (1979). Uncertainties Associated with Global Effects of Atmospheric Carbon Dioxide, ORAV/IEA-79-6 (0).

Siegenthaler, U. and Oeschger, H. (1978). "Predicting Future Atmospheric Carbon Dioxide Levels," Science 199, pp. 388-395.

Shaw, Henry (1978). Attached Appendix (B) of Letter to Dr. E. E. David, Jr. on December 7, 1978.

Steinberg, M., A. S. Albanese and Vi-duong Dang (1978). "Environmental Control Technology for Carbon Dioxide," presented at 71st Annual AICHE Meeting, November 12-16, 1978, Miami, Florida.

Stuiver, M. (1978). "Atmospheric Carbon Dioxide and Carbon Reservoir Changes," Science 199, pp. 263-258.

Terra, Stan (1978). "CO_2 and Spaceship Earth," EPRI Journal July/August, 1978, pp. 22-27.

Williams, J. (1978). "Global Energy Strategies, the Implications of CO_2," Futures, August, 1978, pp. 293-302.

b1798

Table 1

CO_2 EMISSIONS

Fuel	lb CO_2 Emitted* / 1000 Btu Fuel	% of Present CO_2 Output
SNG from Coal	0.35	0
Coal Liquids	0.32	0
Methanol from Coal	0.38	0
H_2 from Coal Gasification	0.38	0
Shale Oil	0.23	0
Bituminous Coal	.21	38%
Petroleum	.15	49%
Natural Gas	.11	13%
Fission/Fusion	0	0
Biomass	0	0
Solar	0	0

* Includes conversion losses where applicable.

c1798

APPENDIX A

ECOLOGICAL CONSEQUENCES OF INCREASED CO_2 LEVELS

From:

Peterson, E.K., "Carbon Dioxide Affects Global Ecology," Environmental Science and Technology 3 (11), 1162-1169 (Nov '69).

1. Environmental effects of increasing the CO_2 levels to 500 ppm. (1.7 times 1860 level)

    - A global temperature increase of 3°F which is the equivalent of a 1°-4° southerly shift in latitude. A 4° shift is equal to the north to south height of the state of Oregon.
    - The southwest states would be hotter, probably by more than 3°F, and drier.
    - The flow of the Colorado River would diminish and the southwest water shortage would become much more acute.
    - Most of the glaciers in the North Cascades and Glacier National Park would be melted. There would be less of a winter snow pack in the Cascades, Sierras, and Rockies, necessitating a major increase in storage reservoirs.
    - Marine life would be markedly changed. Maintaining runs of salmon and steelhead and other subarctic species in the Columbia River system would become increasingly difficult.
    - The rate of plant growth in the Pacific Northwest would increase 10% due to the added CO_2, and another 10% due to increased temperatures.

2. Effects of a doubling of the 1860 CO_2 concentration. (580 ppm)

    - Global temperatures would be 9°F above 1950 levels.
    - Most areas would get more rainfall, and snow would be rare in the contiguous states, except on higher mountains.
    - Ocean levels would rise four feet.
    - The melting of the polar ice caps could cause tremendous redistribution of weight and pressure exerted on the earth's crust. This could trigger major increases in earthquakes and volcanic activity resulting in even more atmospheric CO_2 and violent storms.
    - The Arctic Ocean would be ice free for at least six months each year, causing major shifts in weather patterns in the northern hemisphere.

- The present tropics would be hotter, more humid, and less habitable, but the present temperature latitude would be warmer and more habitable.

b1798

APPENDIX B

FOSSIL FUEL RESOURCES

Oil	- Assume 1.6 trillion barrels of oil potentially recoverable as of 1975 (assuming the future recovery rate to be 40%). The minimum allowable Reserve to Production (R/P) ratio is ten one.
Shale Oil	- Potential of 3.0 trillion B.O.E. but assuming 1977 technology only 200 billion B.O.E. actually recoverable.
Natural Gas	- Approximately 1.6 trillion B.O.E. potentially recoverable. Minimum allowable R/P = 7.1.
Coal	- Potential recoverable reserves equal approximately 12 trillion B.O.E. assuming a conservative 25% recoverability.

APPENDIX C

CONSTRUCTION OF SCENARIOS B AND C
(Scenario A requires no CO_2 emissions control)

1. Scenario B

The CO_2 concentration vs. year curve in Figure 9 was generated by the following equation:

after 1970 (t = 0), then

$$*C = 292 \text{ ppm} + 219 \text{ ppm}/[1 + 5.37 \exp. (-t/24 \text{ years})]$$

where C = concentration in ppm

The curve on the lower section of Figure 9, atmospheric CO_2 increase vs. years, is generated by finding the difference in the concentrations of successive years. This curve gives the maximum yearly increases allowable to stay within the limits placed on this scenario. The amount of fossil fuel that may be consumed in any given year can then be calculated by the lower curve. For example:

In 2100 the maximum allowable CO_2 increase equals 0.2 ppm.

This is equivalent to:

$$\frac{2 \text{ ppm}}{} \times \frac{2.1 \times 10^9 \text{ ton C}}{1 \text{ ppm}} \times \frac{2000 \text{ lb}}{\text{ton}} \times \frac{44 \text{ lb } CO_2}{12 \text{ lb C}} = 3.1 \times 10^{12} \text{ lb } CO_2$$

3.1×10^{12} lb CO_2 may be released by the combustion of:

for coal: $$\frac{3.1 \times 10^{12} \text{ lb } CO_2}{} \times \frac{1000 \text{ Btu}}{.21 \text{ lb } CO_2} \times \frac{1 \text{ B.O.E.}}{5.8 \times 10^6 \text{ Btu}}$$

= 2.5 billion B.O.E. of coal

This scenario is based on the assumption that 50% of CO_2 released each year will always be absorbed by the ocean and the rest will remain in the atmosphere.

*Derived from an equation presented by U. Siegenthaler and H. Oeschger (1978) (see references).

2. Scenario C

The equation for the generation of Figure 11 is derived to be,

after 1970 (t = 0), then

$$*C = 292 \text{ ppm} + 146 \text{ ppm}/[1 + 3.37 \exp.(-t/20 \text{ years})]$$

This scenario is the same as Scenario B only with different limits.

Figure 1

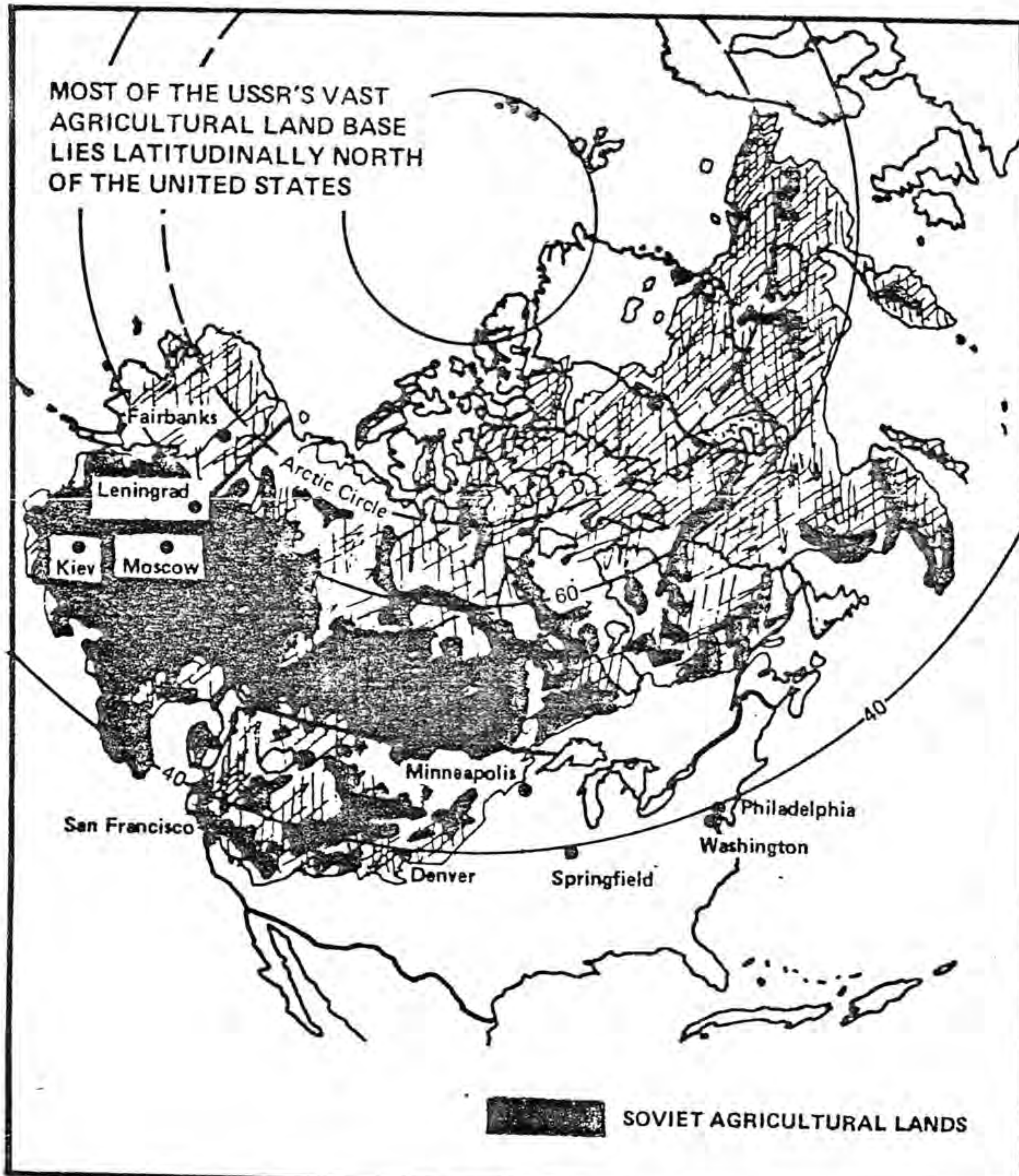

MOST OF THE USSR'S VAST AGRICULTURAL LAND BASE LIES LATITUDINALLY NORTH OF THE UNITED STATES
Fairbanks
Leningrad
Kiev
Moscow
Arctic Circle
60
40
40
Minneapolis
San Francisco
Philadelphia
Washington
Denver
Springfield
SOVIET AGRICULTURAL LANDS

Figure 2

CONCENTRATION OF ATMOSPHERIC CO_2 AT MAUNA LOA OBSERVATORY, HAWAII

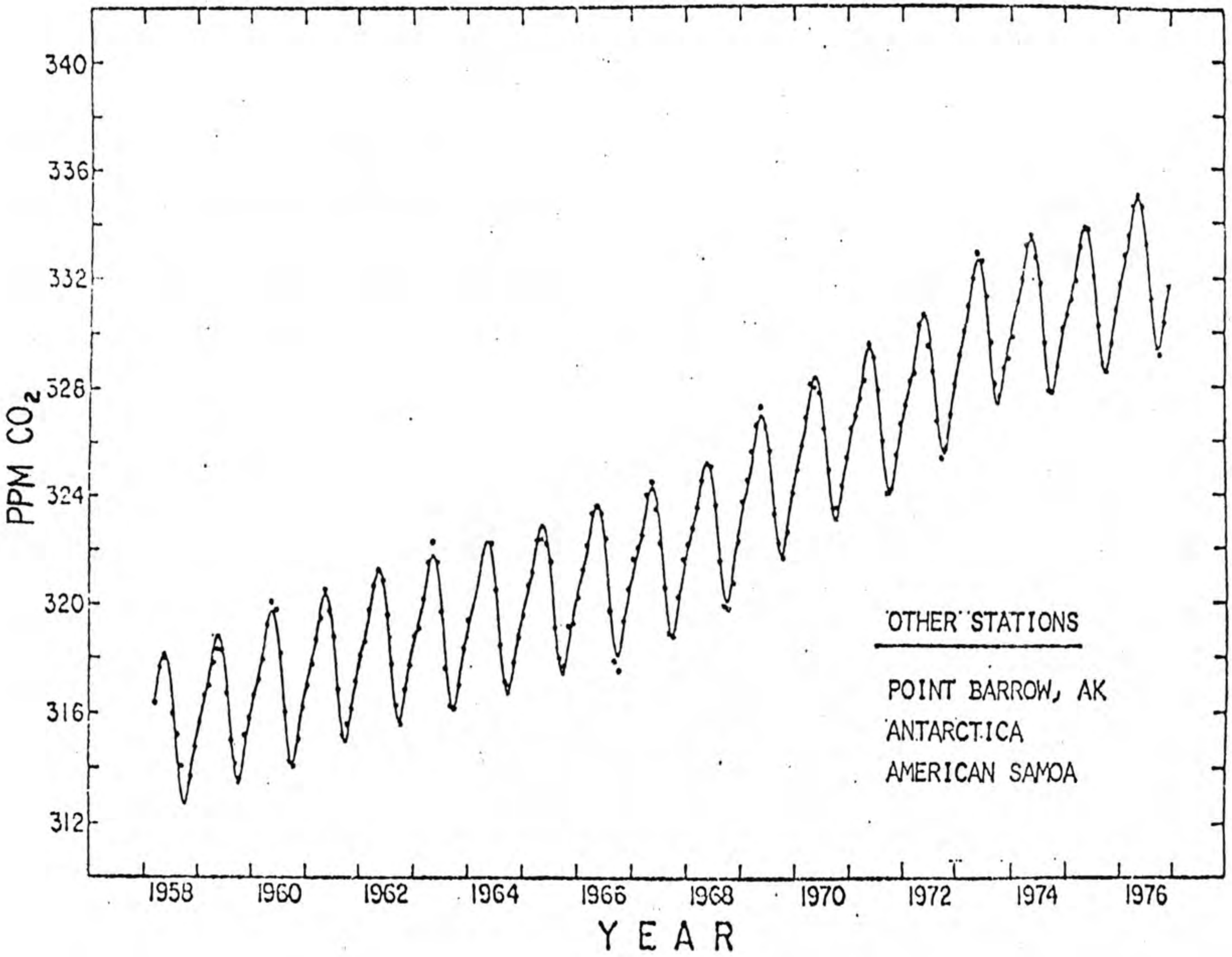


Figure 3

The Carbon Cycle

Current

Fluxes in Gt/a
Pool sizes in Gt

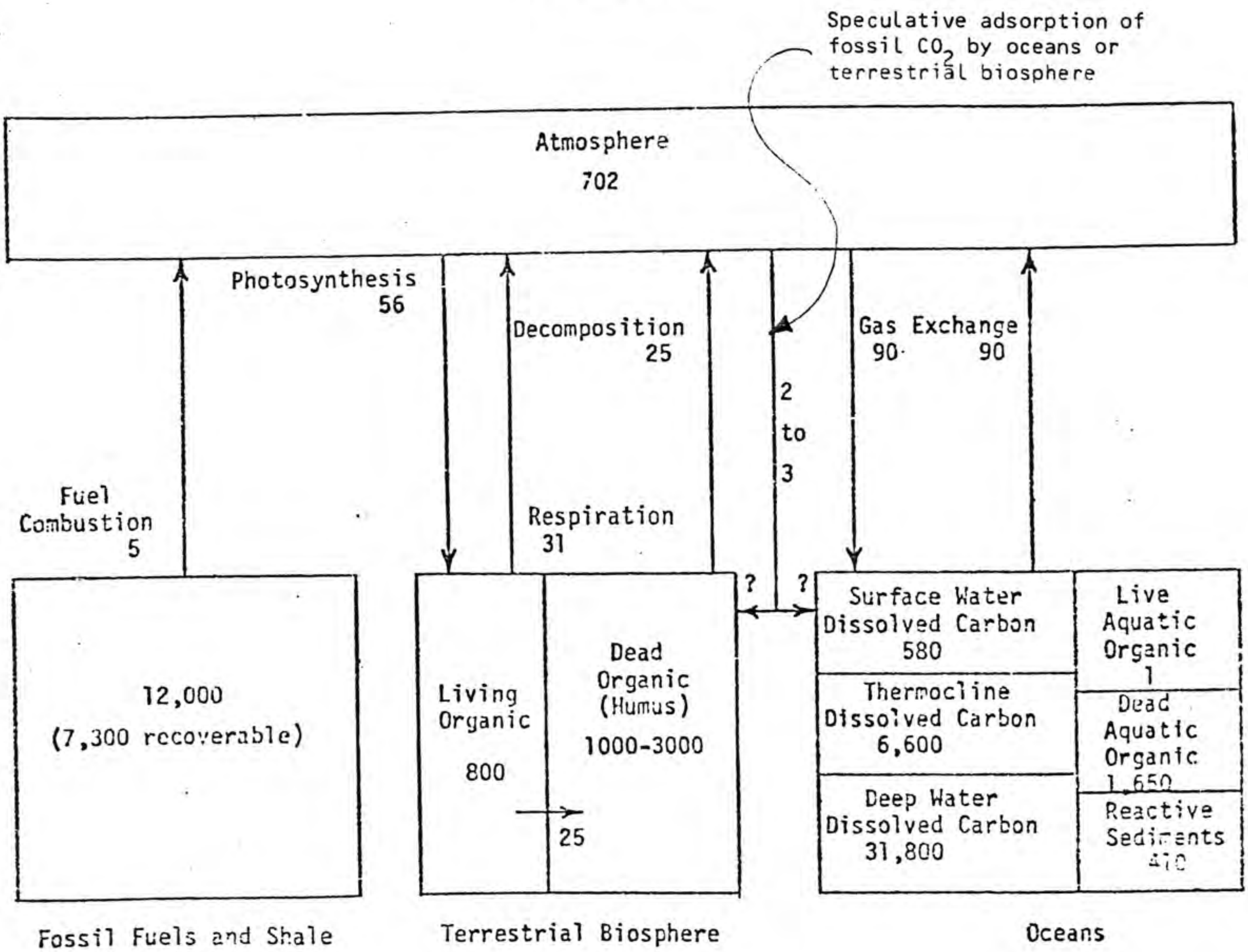


Figure 4

HOW PREDICTED ΔT COMPARES WITH RECENT TEMPERATURES

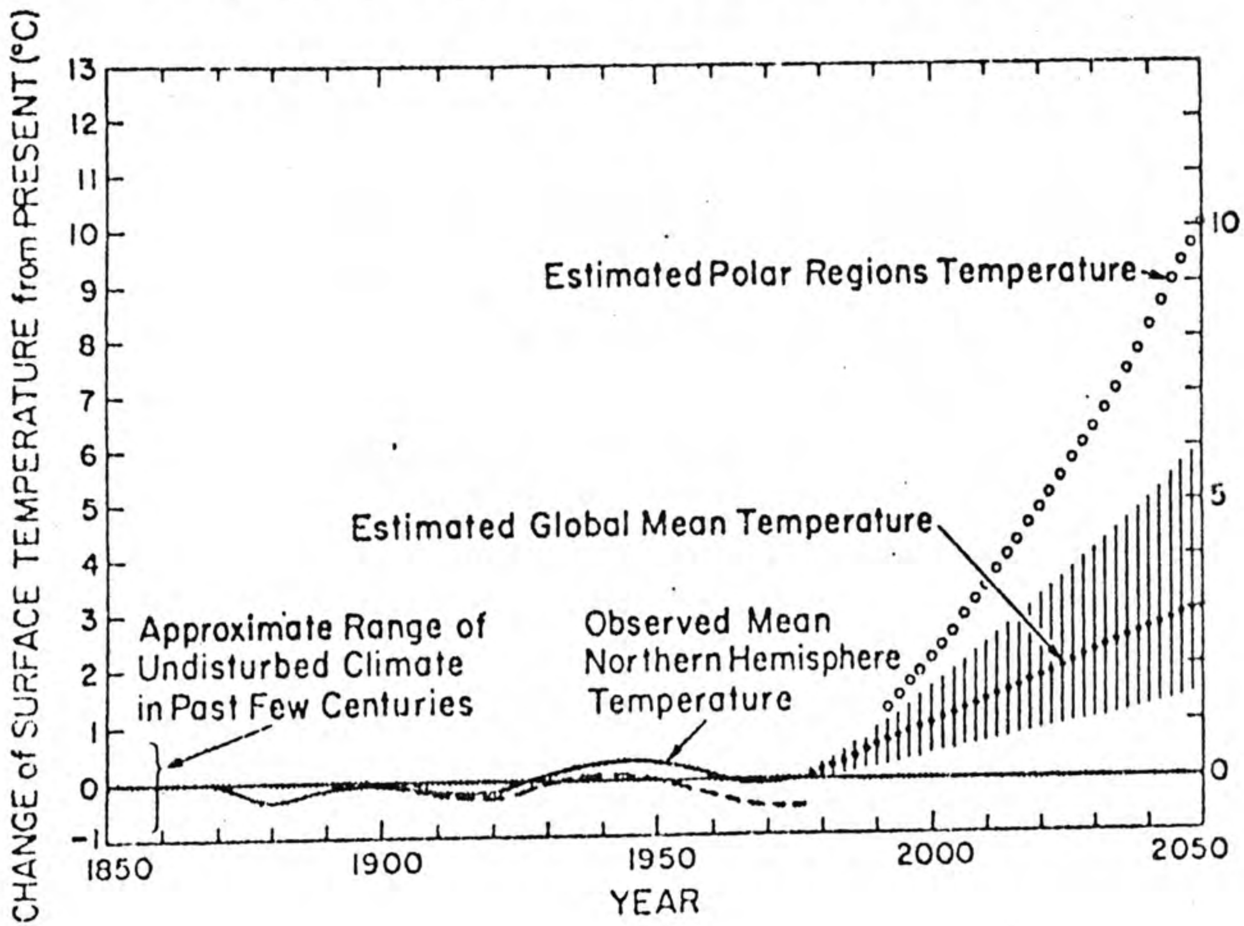


Figure 5

TEMPERATURE EFFECT OF DOUBLING CO_2

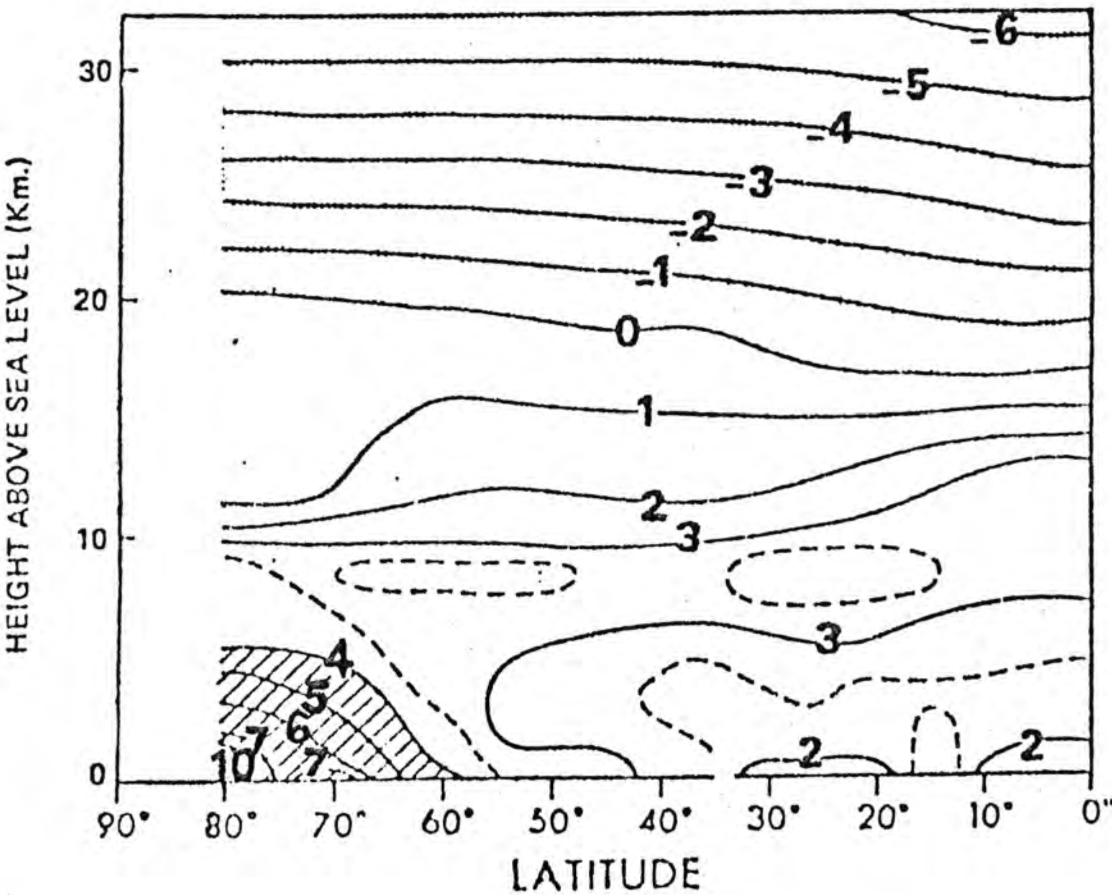


Figure 6

WORLD ENERGY DEMAND BY FUEL

UNLIMITED CO_2 INCREASE
(COAL EMPHASIS)

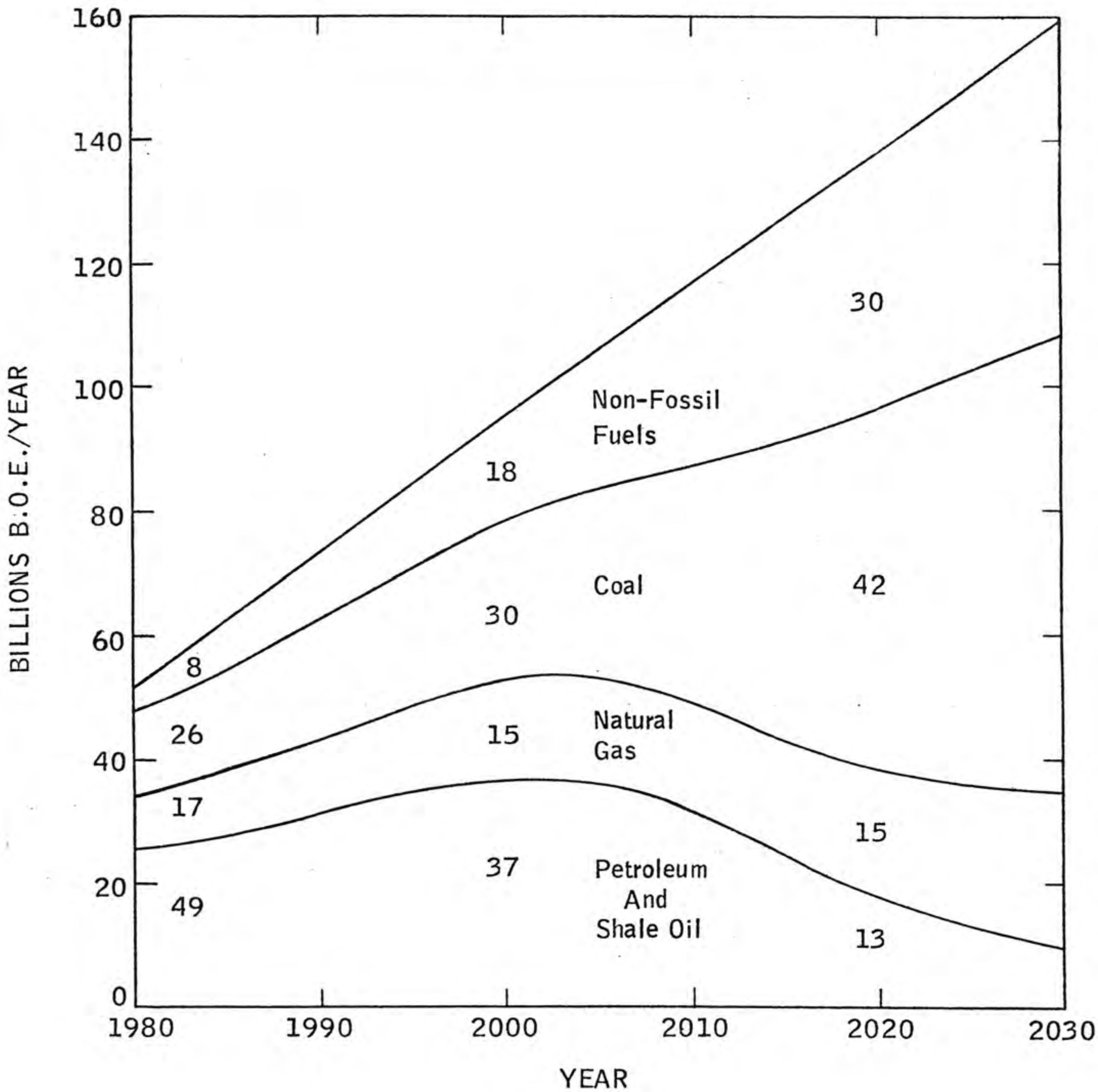


Figure 7

CO_2 IN ATMOSPHERE

RATE OF CO_2 BUILDUP

UNLIMITED INCREASE

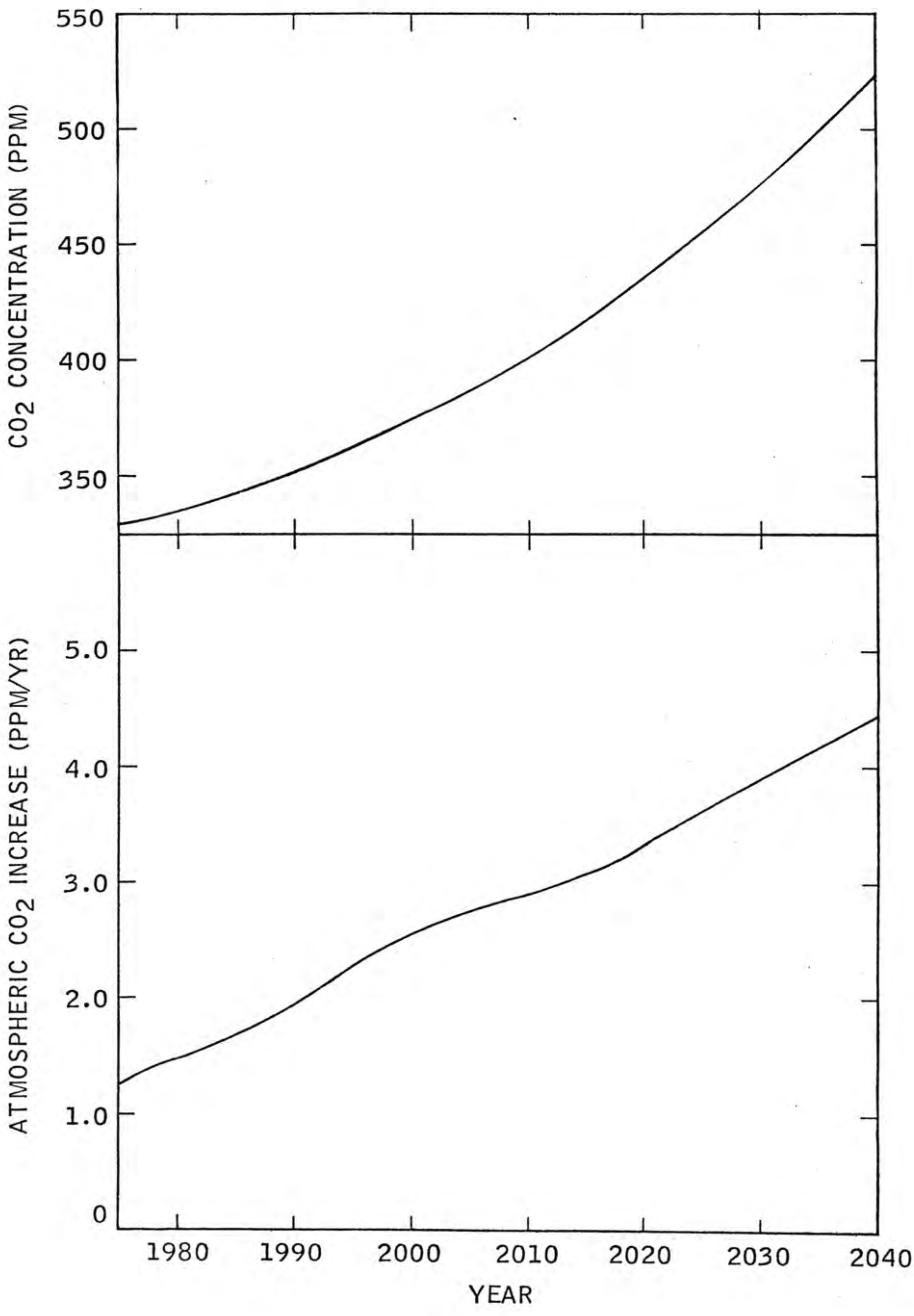


Figure 8

WORLD ENDERGY DEMAND BY FUEL
LIMITED TO A 75% CO_2 INCREASE

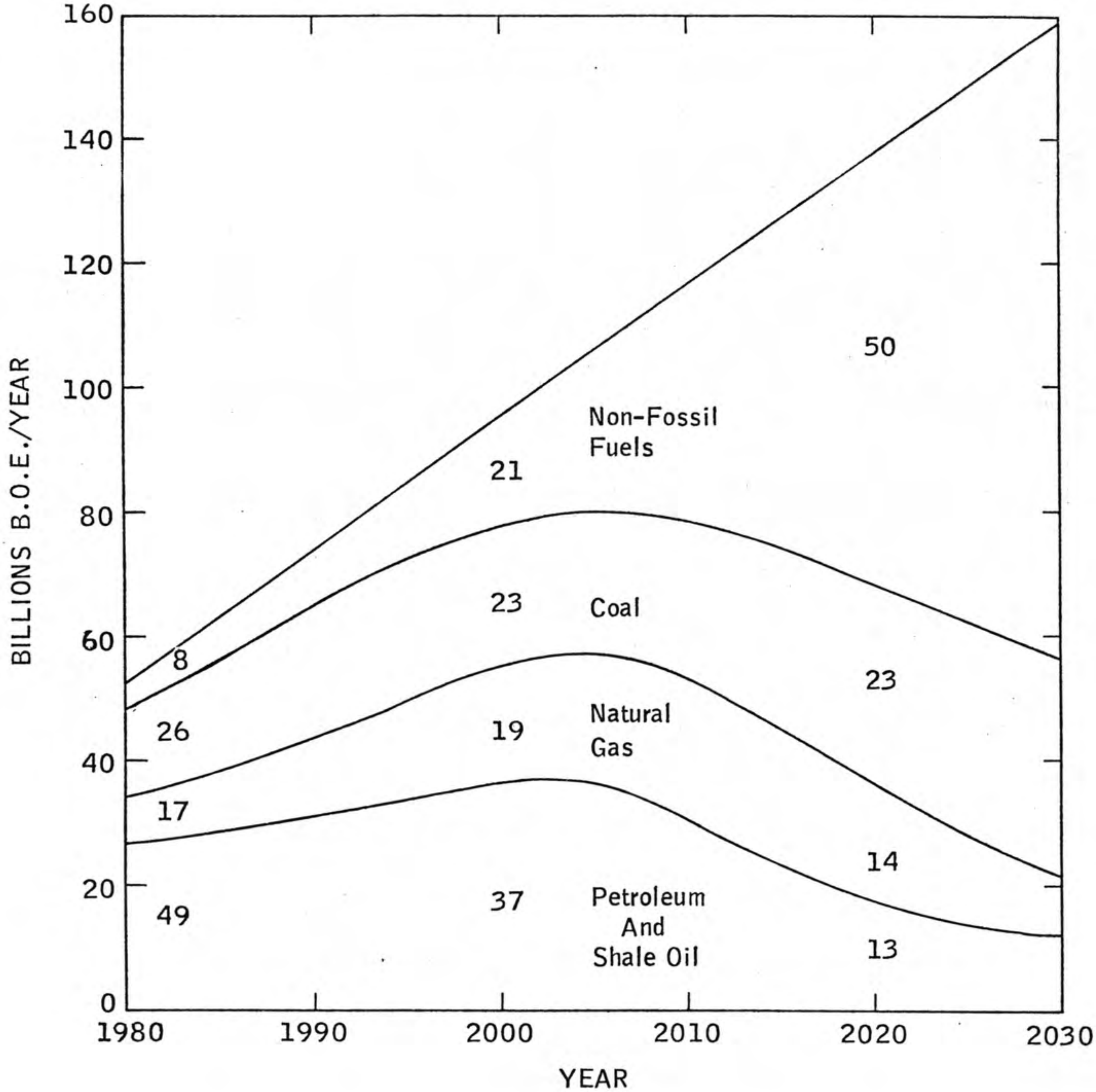


Figure 9

CO_2 IN ATMOSPHERE

RATE OF CO_2 BUILDUP
LIMITED TO 75% INCREASE

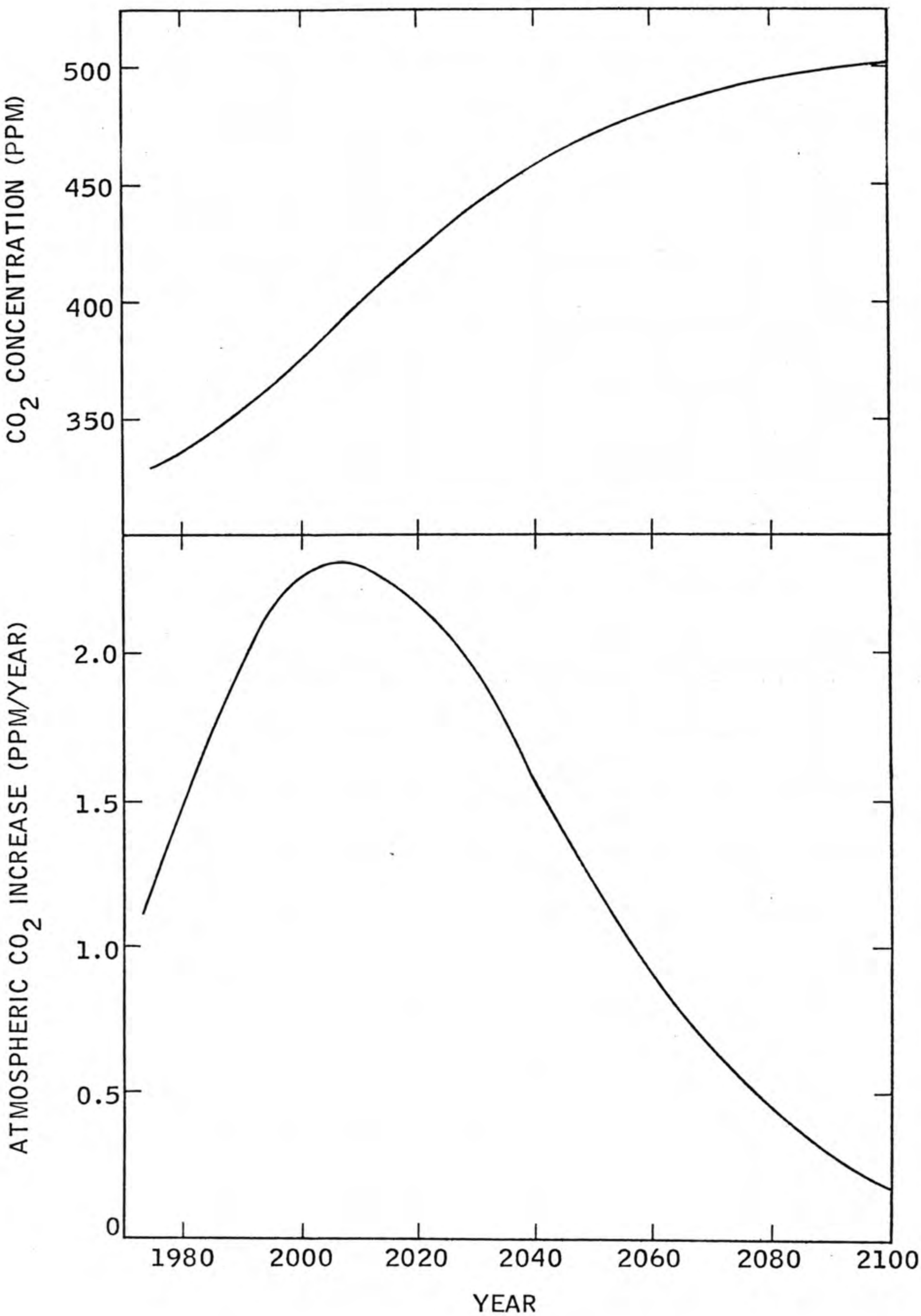


Figure 11

CO_2 IN ATMOSPHERE

RATE OF CO_2 BUILDUP

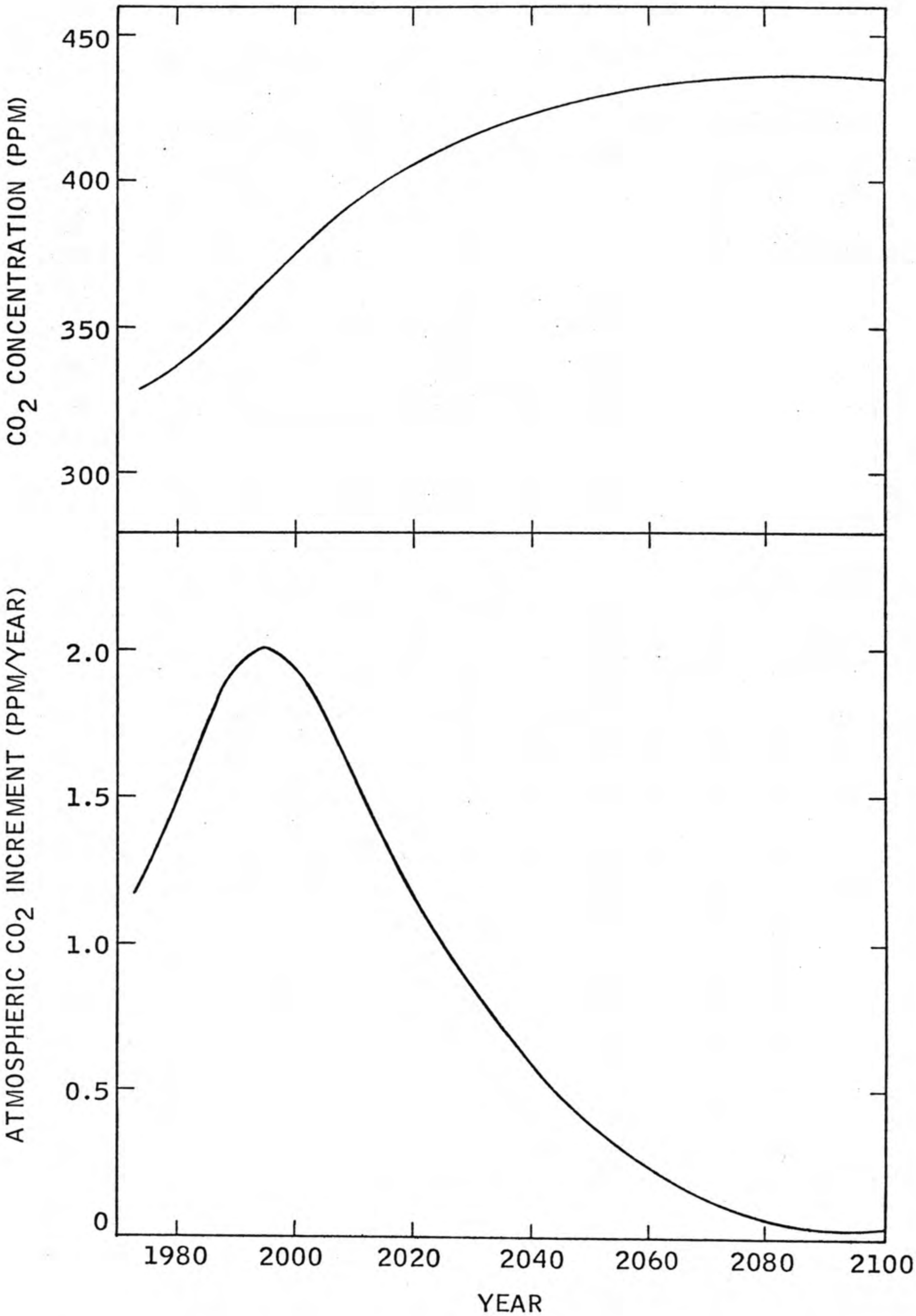


EXHIBIT 17

American Petroleum Institute
2101 L Street, Northwest
Washington, D.C. 20037
202-457-7000

J. J. Nelson
(202) 457-6381

March 18, 1980

To: AQ-9 Task Force

Attached please find a copy of the minutes of the February 9, 1980 AQ-9 Task Force meeting. Please inform me of any errors or omissions.

Cordially,

J J Nelson

Attachment--minutes

/mi

CO_2 AND CLIMATE TASK FORCE (AQ-9)

Minutes of Meeting

9:15 a.m.
Friday, February 29, 1980

Manhatten Room
LaGuardia Airport
New York City, New York

MEMBERS PRESENT

K. Blower, Chairman	SOHIO
B. Bailey	Texaco
H. Shaw	Exxon R&E

OTHERS PRESENT

J. Laurman	Consultant
J. Nelson	API/EAD
C. Showers	SOHIO

OPENING REMARKS

K. Blower, Chairman, opened the meeting by listing the following goals of this meeting:

1. Increase industry's understanding of the CO_2 and climate problem.

2. Determine if there are feasibile and valuable research projects that could be accomplished by API.

3. Establish a mechanism to prepare any needed issue papers.

B. Bailey added the following items for consideration:

1. This Task Force should be the focal point and establish a basis for providing API comments on CO_2 and climate matters.

2. An overall goal of the Task Force should be to help develop ground rules for energy release of fuels and the cleanup of fuels as they relate to CO_2 creation.

CONSULTANT REPORT

Dr. J. A. Laurman, a consultant and a recognized expert in the field of CO_2 and climate,made a presentation to the Task Force entitled, "The CO_2 Problem; Addressing Research Agenda Development."

An outline is included as Attachment A.

In addition, a complete technical discussion, led by Dr. Laurman identified the problem, discussed the scientific basis and technical evidence of CO_2 buildup, impact on society, methods of modeling and their consequences, uncertainties, policy implications, and conclusions that can be drawn from present knowledge. A series of summary charts are attached as Attachment B.

API RESEARCH NEEDS

One area of possible API research was identified: Preparatory research to be able to answer questions dealing with the CO_2 problem and synthetic fuels.

COMMENTS ON DOE TECHNICAL PAPER

K. Blower and Bruce Bailey will modify the draft API letter back to DOE concerning an article submitted to the Task Force for comment. When the Task Force has approved the letter, it will be coordinated within API staff.

OTHER BUSINESS

The Task Force should set up a rationale and system for review of technical articles and responses to inquiries.

One potential area for R&D was discussed by the Task Force: "Investigate the Market Penetration Requirements of Introducing A New Energy Source into World Wide Use." This would include the technical implications of energy source changeover, research timing and requirements.

The meeting was adjourned at 4:25 p.m.

Prepared by:

J J Nelson

Jimmie J. Nelson

ATTACHMENT A.

THE CO_2 PROBLEM; ADDRESSING RESEARCH AGENDA DEVELOPMENT

The difficulties of dealing with the pragmatic questions related to the CO_2/fossil fuel problem all relate to certain general features, these having A) high impact cost, B) large uncertainty, and being C) far distant and D) global. The problem is interdisciplinary in its scientific aspects and it has ramifications in many economic sectors and in most nations. Therefore, not only is addressing it difficult in anlytic terms, but the mulitiplicity of possible interest groups that can be affected means that choice of what constitute the critical research issues depends on the user. In the most general terms we can subdivide the motivational aspect into those who see the need as to

A) better understand the CO_2/climate system, resulting in an ability to predict a) short range and b) long range effects.

or to

B) assess the present day importance of the future impact, as viewed

i) from a world viewpoint

ii) by national entities

iii) by specific industrial sectors or interest groups

Highest priority investigations depend on which of these groups is involved. In particular, a highly relevant aspect for all of these groups is the influence of present and future information on public perception and governmental attitudes regarding the problem and the resultant effect on energy policy.

Instead of attempting to research all aspects of the CO_2 problem that bear on the concern of any particular group, we may select a feature that appears to be particularly important to that sector - for example, nuclear energy proponents might wish to address the problem of market penetration time lags as the most critical for making their case.

A) Reducing uncertainty in projections

CO_2 input

a) deforestation, past present and future.

b) effect of various energy use policies - coal, oil shale, nuclear, biomass, solar, synthetics.

c) turn-around scenarios for non-carbon based fuel use, impact calculations.

d) remedial measures: biomass, scrubbing, bacterial enzymes, fertilizing oceans.

Carbon cycle

a) CO_2 growth and photosynthesis

b) missing CO_2 since - detritus, humus, regrowth of deforested areas, oceans, non-stationary biosphere.

c) validity of box-model projections in short (50 yr) range.

d) organic material in oceans (detritus, dissolution, nutriant limitations)

e) estuarian regions

f) ground water

g) carbonate distribution

h) use of tracers

i) cataloguing on the biosphere

j) climatic change feedback effects - ocean temperature, plant growth.

Climate modeling

a) ocean dynamics

b) simplifying models

c) feedback effects : clouds, sea ice, vegitation change(albedo).

d) regional climatic change

B) Impact of climatic change

Socio-economic

I) General problems:

a) how to make estimates of costs of large perturbations, even assuming climatic changes are known?

b) how do we discount the future?

c) geopolitical problems, either from climatic change or from remediation measures

d) building in resilience. Can severity be versed in terms of critical rates of change of forcing of the societal system? Is a generic non-specific formulation possible?

II) Immediate policy questions. The physical facts agree on the probability of large effects 50 years away, but with large probable error. Source of the uncertainty arises from deforestation, poor climate models and uncertainty in CO_2 input (energy projections). The first may be settled in a year or two; the second will not. Hence we have to treat an unsure situation, which may be possible via decision analysis if error distribution can be quantified. This has not been done for impact costs, so first

a) can it be? If yes, there still remain two major difficulties:
b) what are market penetration times for new energy sources? and
c) what future (social) discounting rate should be used?

If fossil fuel use rates are reduced to 2% p.a. or under, it looks as if the immediate problem is considerably eased (but needs checking). So another question is

d) what is the 50 year future of fossil fuel use?

Of more parochial interest is

e) what roles do the different catagories of fossil or synthetic fuel play in future projections?

<u>The Natural Biosphere</u>

<u>The Managed Biosphere</u>

REASONS FOR INCREASED CONCERN WITH THE CO_2 PROBLEM

- DEVELOPMENT OF RELIABLE ATMOSPHERIC CO_2 GROWTH RATE MEASUREMENTS
- ITS CORRELATION WITH GLOBAL INDUSTRIAL CO_2 EMISSIONS, MOSTLY FROM FOSSIL FUEL COMBUSTION
- SCIENTIFIC CONSENSUS ON THE POTENTIAL FOR LARGE FUTURE CLIMATIC RESPONSE TO INCREASED CO_2 LEVELS
- REALIZATION THAT REMEDIAL ACTIONS WOULD TAKE A LONG TIME TO BECOME EFFECTIVE

ATTACHMENT B

OBSERVATIONAL EVIDENCE - CONCLUSIONS

- TWENTY YEARS OF GOOD CO_2 DATA, BUT ESSENTIALLY FROM ONE SOURCE
- PRESENT ATMOSPHERIC CO_2 CONCENTRATION = 335 ppm
  PRE-INDUSTRIAL (1860) " ≈ 290 ppm
- CURRENT GROWTH RATE = 4.3% p.a. OF INCREASE SINCE 1860
- STRONG EMPIRICAL EVIDENCE THAT RISE CAUSED BY ANTHROPOGENIC RELEASE OF CO_2, MAINLY FROM FOSSIL FUEL BURNING
- ATMOSPHERIC RETENTION IS 56% OF RELEASE, ASSUMING NO EFFECTS FROM DEFORESTATION

ENERGY USE PROJECTIONS - CONCLUSIONS

- AVERAGE GROWTH RATE 3-4% p.a. FOR NEXT FIFTY YEARS, FOSSIL FUEL SLIGHTLY LESS
- THIS IS NOT CONSISTANT WITH LONG TERM PAST TREND
- PROJECTED CO_2 RELEASE ~~RATE~~ INCREASE (PROPORTIONAL TO INTEGRATED FOSSIL FUEL OUTPUT) CLOSE TO 3% p.a. UNTIL MID-21ST CENTURY; SUBJECT TO ERROR OF ABOUT ± 1% p.a.
- EFFECT OF FOSSIL FUEL DEPLETION MINOR IN NEXT FIFTY YEARS

CARBON CYCLE - CONCLUSIONS

- POSSIBLE CO_2 RELEASE CONTRIBUTION FROM DEFORESTATION, PERHAPS RIVALLING FOSSIL FUEL SOURCE
- ALL CARBON CYCLE MODELS BEHAVE LINEARLY UP TO 3-4 TIMES PRE-INDUSTRIAL ATMOSPHERIC CO_2 LEVELS
- HENCE GIVE THE SAME PROJECTED ATMOSPHERIC CO_2 LEVELS FOR THE SAME INPUT
- FOSSIL FUEL DEPLETION EFFECTS SMALL
- DEFORESTATION EFFECT ON PROJECTIONS ONLY SIGNIFICANT IF IT BECOMES DEPLETED
- CO_2 "DOUBLING" DATE IS 2038 AT A 3% p.a. GROWTH OF ATMOSPHERIC RELEASE RATE
- ERROR IN THIS ESTIMATE IS SMALL COMPARED WITH OTHER SOURCES OF ERROR

CLIMATE MODELING - CONCLUSIONS

- GLOBAL AVERAGED 2.5°C RISE EXPECTED BY 2038 AT A 3% p.a. GROWTH RATE OF ATMOSPHERIC CO_2 CONCENTRATION
- LARGE ERROR IN THIS ESTIMATE - 1 IN 10 CHANCE OF THIS CHANGE BY 2005
- NO REGIONAL CLIMATE CHANGE ESTIMATES YET POSSIBLE
- LIKELY IMPACTS:

  1°C RISE (2005): BARELY NOTICEABLE

  2.5°C RISE (2038): MAJOR ECONOMIC CONSEQUENCES, STRONG REGIONAL DEPENDENCE

  5°C RISE (2067): GLOBALLY CATASTROPHIC EFFECTS

UNCERTAINTY IN ESTIMATES

1) CARBON CYCLE MODELING - MINOR
2) DEFORESTATION - MAJOR EFFECT ONLY IF RATE IS LARGE <u>AND</u> DEPLETION SETS IN
3) NATURAL CLIMATE VARIABILITY - SMALL, ABOUT 0.5° C IN 50 YEARS
4) OTHER ANTHROPOGENIC SOURCES - LESS THAN CO_2, BUT POTENTIALLY MAJOR IF CONSIDERED IN TOTO
5) EFFECT OF A ± 1% VARIATION IN FOSSIL FUEL GROWTH RATE RELATIVELY MINOR
6) CLIMATE MODELING ERROR VERY LARGE; ALLOWANCE IN POLICY ANALYSIS ESSENTIAL

POLICY IMPLICATIONS

- GLOBAL PROBLEM, BOTH IN SOURCE AND FOR REMEDIES
- TIME SCALE FOR SIGNIFICANT IMPACT, VERY ROUGHLY 50 YRS
- HIGH RISK, HIGH UNCERTAINTY SITUATION, RELATIVELY FAR AWAY
- TIME FOR ACTION ? MARKET PENETRATION TIME THEORY SAYS
  THERE IS <u>NO</u> LEEWAY

CONCLUSIONS

- AT A 3% PER ANNUM GROWTH RATE OF CO_2, A 2.5°C RISE BRINGS WORLD ECONOMIC GROWTH TO A HALT IN ABOUT 2025.

Even if this estimate is grossly wrong it is still probable that

- WHETHER THERE ARE GROUNDS FOR IMMEDIATE RESPONSE TO THE THREAT DEPENDS ON THE VALIDITY OF THE LONG MARKET PENETRATION TIME CONCEPT.
- EVEN IF THE LATTER IS APPLICABLE, PRESENT DAY SIGNIFICANCE OF THE IMPACT DEPENDS STRONGLY ON CHOICE OF A FUTURE DISCOUNTING FACTOR.
- NEED FOR IMMEDIATE POLICY ACTION HINGES ON THESE LAST TWO FEATURES.

EXHIBIT 18

GENERAL - 184-1-1B
INTER-OFFICE CORRESPONDENCE

DATE August 18, 1981

TO W. Glass	REFERENCE
FROM R. W. Cohen	SUBJECT

I have looked over the draft of the EED reply to the request from O'Loughlin. The only real problem I have is with the second clause of the last sentence in the first paragraph: "but changes of a magnitude well short of catastrophic..." I think that this statement may be too reassuring. Whereas I can agree with the statement that our best guess is that observable effects in the year 2030 are likely to be "well short of catastrophic", it is distinctly possible that the CPD scenario will later produce effects which will indeed be catastrophic (at least for a substantial fraction of the earth's population). This is because the global ecosystem in 2030 might still be in a transient, headed for much more significant effects after time lags perhaps of the order of decades. If this indeed turns out to be case, it is very likely that we will unambiguously recognize the threat by the year 2000 because of advances in climate modeling and the beginning of real experimental confirmation of the CO_2 effect. The effects of such a recognition on subsequent fossil fuel combustion are unpredictable, but one can say that predictions based only on our knowledge of availability and economics become hazardous.

I would feel more comfortable if the first paragraph concluded with a statement to the effect that future developments in global data gathering and analysis, along with advances in climate modeling, may provide strong evidence for a delayed CO_2 effect of a truly substantial magnitude, a possibility which increases the uncertainty surrounding the post-2000 CPD scenario.

ROGER W. COHEN

RWC:tmw

Attachment

cc: H. N. Weinberg
A. J. Callegari

ENERAL 154-1-1B
TER-OFFICE CORRESPONDENCE

DATE 8/14/81

O See Below	REFERENCE
ROM W. Glass	SUBJECT

J. F. Black
R. W. Cohen
S. A. Diamond
H. Shaw

Morey O'Loughlin has asked Ed David for ER&E's views on the realism of CPD's projections for fossil fuel combustion out to 2030 (attached) in view of potential "greenhouse" and "acid rain" problems. I have been asked to draft a short reply.

A preliminary draft for EED's reply is attached. It is based not on any calculations but on my "understanding" of what I think I've heard you say and write in the past. I would appreciate your reviewing this preliminary draft very critically and letting me know promptly of any changes you would like to see. EED wants to get an answer back to MEJO'L by August 21.

Thank you for your cooperation.

WG:bl
Attachments

c: T. K. Kett

DRAFT
EED TO MEJO'L

You asked about our views on possible emission consequences of the CPD-projected fossil fuel consumption levels out to 2030. Much is still unknown about the sources and sinks for atmospheric CO_2, as well as about the climatic effect of increasing CO_2 levels in the air, so that prognostications remain highly speculative. The models that appear most credible (to us) do predict measurable changes in temperature, rainfall pattern, and sea-level by the year 2030 for the postulated fossil fuel combustion rates, but changes of a magnitude well short of catastrophic and probably below the magnitude that need trigger otherwise non-economic responses to the problem of energy supply.

The fossil fuel contribution to the localized problem of acid rain appears handlable by limiting the release of SO_x, NO_x, and chlorides to the atmosphere--which would decrease but by no means eliminate the economic advantage of fossil fuels.

We would be happy to discuss this with you in greater detail.

INITIAL PROJECTION
WORLD ENERGY SUPPLY

(EXCLUDES CPE)

AVERAGE GROWTH, %/YEAR

	1960-1979	1979-2000	2000-2030
CONV. OIL	5.6	0.2	(1.5)
SYNTHETICS	—	14.6	6.3
GAS	4.9	1.9	0.7
COAL	0.8	3.6	1.9
NUCLEAR	7.0	8.9	4.8
OTHER	4.0	3.5	1.0
TOTAL	4.3	2.2	1.7

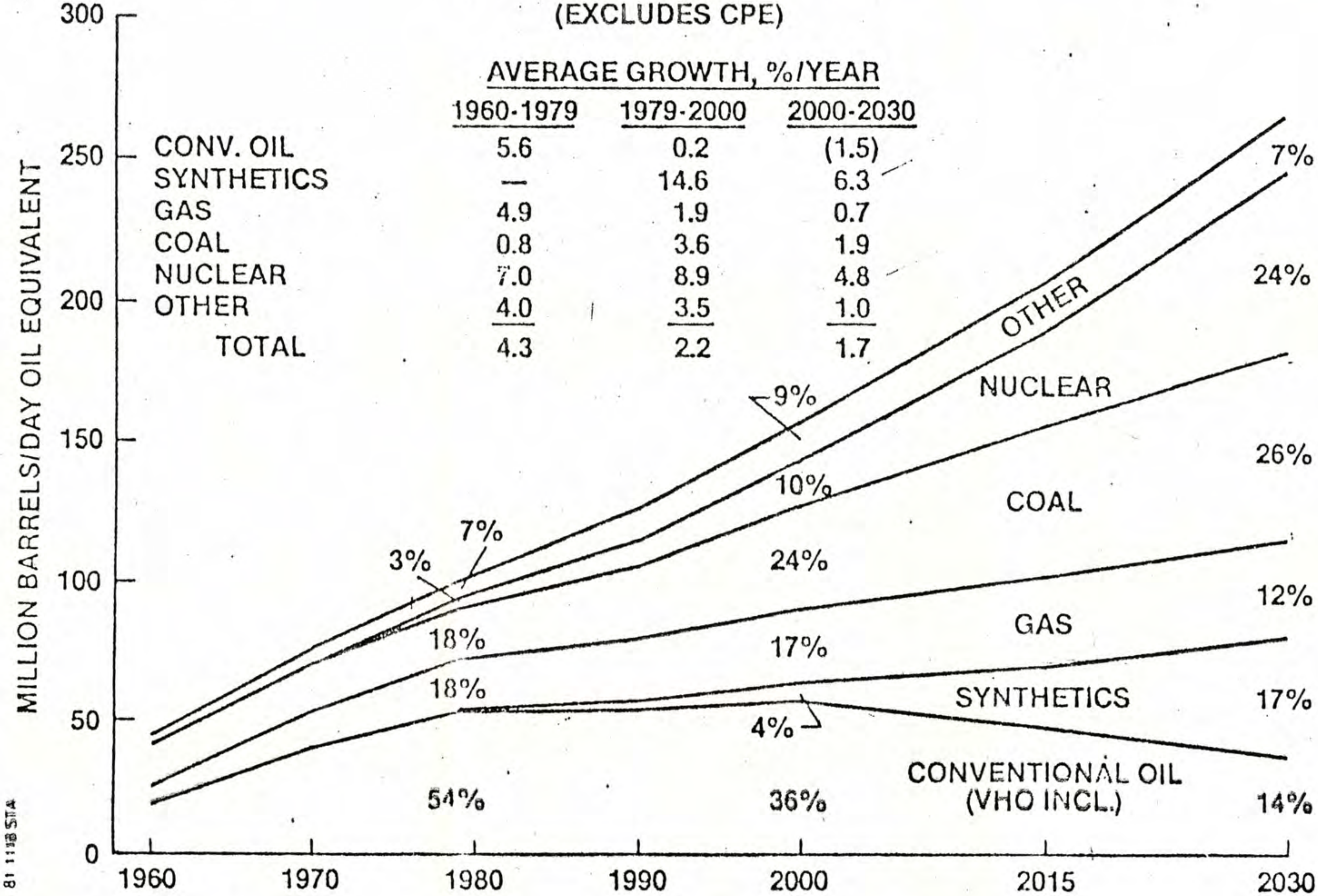


EXHIBIT 19

GENERAL - 154-1-1B

INTER-OFFICE CORRESPONDENCE

DATE May 15, 1981

TO Dr. E. E. David, Jr.	REFERENCE
FROM Henry Shaw	SUBJECT CO_2 Position Statement

In case the issue comes up at the San Francisco Symposium, attached is a brief summary of our current position on the CO_2 Greenhouse effect.

HS:ksc
Attachment

c: R. E. Barnum
C. M. Eidt, Jr.
D. Fiske
L. E. Furlong
H. C. Hayworth
T. K. Kett
P. J. Lucchesi
F. B. Sprow
H. N. Weinberg
G. O. Wilhelm
M. Held

PRELIMINARY STATEMENT OF EXXON'S POSITION ON THE GROWTH OF ATMOSPHERIC CARBON DIOXIDE

Position:

There is sufficient time to study the problem before corrective action is required.

- An indication of the average global temperature increase due to CO_2 will not be measurable above normal climatic fluctuations (noise) until about 2000.
- Effective energy conservation and high price for fossil fuels over the last few years have now delayed the projected doubling time of CO_2. We estimate now that the doubling time is about 100 years.
- This permits time for an orderly transition to non-fossil fuel technologies should restrictions on fossil fuel use be deemed necessary.

Synthetics Impact:

There is no reason to stifle or halt development of synthetics industry.

- Impact of synthetics on doubling time is very small (4%/yr average synthetics growth rate reduces doubling time by only 5 years = 15 MB/D synthetics in 2010).
- Coal liquids contribute about 100% more CO_2 than burning coal directly; shale oil about 50% more.

Background:

- Average atmospheric CO_2 increased 7% since 1957 (315 to 338 ppm). We project CO_2 will reach about 380 ppm by 2000.
- Atmospheric CO_2 will double in 100 years if fossil fuels grow at 1.4%/a.
- $3^{\circ}C$ global average temperature rise and $10^{\circ}C$ at poles if CO_2 doubles.
  - Major shifts in rainfall/agriculture
  - Polar ice may melt
- U. S. Government conducting 10-year study at 10M$/a to reduce large scientific uncertainties and recommend appropriate energy policy.
- ER&E contributing to the research effort by monitoring atmospheric and oceanic CO_2 from a tanker.

EXHIBIT 20

Climate Models and CO_2 Warming A Selective Review and Summary

AMERICAN PETROLEUM INSTITUTE
MARCH 1982

API PUB. NUMBER 4347

American Petroleum Institute
2101 L Street, Northwest
Washington, D.C. 20037

4.00
99/k

Lamont-Doherty Geological Observatory
(Columbia University)
Palisades, New York 10964

CLIMATE MODELS AND CO_2 WARMING

A Selective Review and Summary

Prepared for the American Petroleum Institute

by

Alan Oppenheim and
William L. Donn

Lamont-Doherty Geological Observatory (Columbia University)
Contribution No. 3310

March 16, 1982

CONTENTS

SUMMARY

This report is a selective summary and discussion of the types of models that have been applied to the prediction of the anthropogenic warming of the atmosphere. All of the quantitative predictions involve only the CO_2 effect although it is recognized that other trace gases may contribute from 50 to 100 percent additional warming. The types of models discussed are, from simple to complex: radiation balance, energy balance, radiative-convective, thermodynamic and general circulation models. The results given in the summary table below have been generated by the most physically complete versions of the models in each category. Additional results, discussed in the report, are omitted from this selection. It seems clear from the discussion herein that all models are still sufficiently unrealistic that a definitive evaluation of the problem requires continued effort.

Table 1.

Model Predictions of 2 × CO_2 Warming of Atmosphere

Model Type and Source	Mean Surface Effect	High-Latitude Effect
Radiation Balance		
Jason Group [2]	Globe: 3.0°C	
Energy Balance		
Jason Group [2]	Globe: 2.4°	7.5°C
Budyko [12]	Globe: 3.1°	9.0
Radiative-Convective		
Augustsson & Ramanathan [18]	Globe: 2°	
Hansen *et al.* [17]	Globe: 2.8°	
Hummel and Reck [39]	Globe: 2.1°	
Thermodynamic		
Adem (Preliminary)	Hem: 0.6°	2°
General Circulation Model		
Manabe & Stouffer [26]	Globe: 2°	7°
Hansen *et al.* [1]	Globe: 3.5°	7°

I. INTRODUCTION

In this report we summarize and discuss with some qualitative evaluation the types of models that have been applied to the prediction of the atmospheric warming consequent upon the increasing CO_2 content of the atmosphere. The examples selected in each of the climate model categories are those that have been developed to the highest state of the art in each category at this time. The report is organized so as to first explain the problem, including an explanation of what is meant by climate, followed by a qualitative summary of the types of models in order of increasing complexity. This is followed by a discussion of the key scientific problems involved, namely the quantitative evaluation of the increased "greenhouse effect". After this discussion a more detailed presentation of the appropriate climate models is given followed by an appraisal of each of the models and categories discussed.

Carbon dioxide is the most studied of the combustion gases since it plays an important role in the interaction between the sun's radiation and the atmosphere. The carbon dioxide concentration has increased steadily since the beginning of the industrial revolution from about 290 parts per million (ppm) to about 340 ppm today (1981). It is expected to double some time in the next century. Just when depends on the particular estimate of the level of increasing energy use per year and the mixture of carbon based fuels [1, 2]. None of these estimates includes the role of the oceans and the biosphere as sources or sinks of CO_2 since the mechanisms of their exchange with the atmosphere are too uncertain at this time. Climate modelers begin with the assumption that atmospheric CO_2 will double (with corresponding increases in other combustion gases) and try to predict what climate changes will occur.

They all predict some kind of increase in temperature within a global mean range of 4°C. The consensus is that high latitudes will be heated more than the equator and the land areas more than the oceans. Such a warming can have serious consequences for man's comfort and survival since patterns of aridity and rainfall can change, the height of the sea level can increase considerably and the world food supply can be affected. The detailed consequences of a CO_2 warming are not yet known. The conclusion is that optimum forecasting of climate changes is a necessity for any realistic long term planning by government and industry.

II. THE NATURE OF CLIMATE AND CLIMATE MODELS

An operational definition of 'climate' is that it is a time-mean state of the atmosphere [3]. Time means are averaged over a given period of time such as 30 days, a season, a year, etc. 'Climate changes' refer to changes of state of the atmosphere over intervals greater than the averaging time.

'Climate models' are mathematical descriptions of the earth-atmosphere system as it is driven by the radiation from the sun. The models range in complexity from a crude picture of the earth as a uniform rotating ball in radiation balance with the solar radiation to the complex general circulation models (GCM) that treat atmospheric dynamics by numerical solutions of fluid dynamical equations. Regardless of complexity, all climate model studies indicate that a doubling of CO_2 will produce a significant increase in the global and annual mean temperature of the earth. Climate model predictions range from 0.6°C to over 4°C, depending more on the physical assumptions than upon the complexity of the model. Several empirical studies [4, 5] give a lower estimate of about 0.26°C. There is sufficient uncertainty in the range

of predictions to leave the consequences of the CO_2 doubling in considerable doubt. The difference between the low end of 0.26°C and the high end of ~4.°C has obvious consequences regarding the amount and speed of polar ice melting and the degree of sea level rise. Other uncertainties are the effect of the warming on: snow and sea-ice cover, the distributions of temperature, rainfall and aridity over the globe, the ocean circulation and oxygen budget, and the related world food supply [1, 6].

A summary of the models to be given further elaboration in Section III is given here for a quick overview of approaches to the CO_2 problem. These do not exhaust the different kinds of models used for climate studies but they are the principal tools, either singly or in combination, applied for predicting the outcome of a CO_2 doubling. (Schneider and Dickinson [3] give a thorough and readable survey of the many approaches to climate modeling that is still current.)

A. The Lowest Order: Radiation Balance Model

In this model the earth is treated as a uniformly rotating sphere with a homogeneous atmosphere in radiative equilibrium with the sun's energy flux. What this means is that the sun bathes the earth with radiation (that is primarily in the visible), that the earth absorbs some of that radiation and in the equilibrium state reradiates it back to space with a spectrum that is primarily in the infrared. All that is needed to compute the "effective radiation temperature" of the earth T_e is to give the known solar energy flux at the top of the atmosphere and that fraction of the solar flux absorbed by the earth-atmosphere system and radiated back as infrared radiation.

It turns out that the mean surface temperature of the earth T_s is about 30°K larger than T_e. This is accounted for by the "greenhouse gases" that absorb and trap thermal (infrared) energy in the atmosphere. Some atmospheric structure must be added to the originally simple picture to compute the absorption of the constituent gases and to maintain the mechanical stability of the lower troposphere. The model as amended is used to estimate a global warming due to the doubling of CO_2 when the remaining physics is unchanged.

B. Energy Balance Models (EBM)

These models add a latitude dependence by dealing with quantities such as surface temperature, heat capacity and albedo that are averaged over a complete latitude strip. One more term is needed to balance the energy equation in each strip. The new term represents horizontal heat transported out of the strip by fluid motions. In equilibrium, the energy balance for each strip would now read: (net transport out) + (infrared out) = (solar in). The transport term is usually parameterized as a diffusion operator (familiar from ordinary heat transfer theory).

Energy balance models have the added attraction that they can be used to estimate the latitude distribution of a CO_2 warming with its effects on the polar ice caps. As with the original radiation balance model, separate calculations with vertical structure in the atmosphere are required to give the infrared terms. The EBM diffusion equation itself, however, admits only a latitude dependence in the equilibrium case with the addition of a time dependence when seasonal and other time varying conditions are treated.

C. Radiative - Convective Models

Radiative-convective models are more complex versions of the radiation balance model described above. Physical parameters are treated as global averages with spatial variation only in the vertical direction. Mathematical computations are performed for convenience in a plane parallel configuration. The atmosphere is divided up into many uniform layers for numerical computation. For such models the principal equations to be solved are those of radiative transport with the convective part appearing as adjustments to the temperature structure to prevent the lower troposphere from becoming mechanically unstable. These models are applied principally to numerical experimentation in which atmospheric parameters can be varied one at a time to estimate the sensitivity of the atmosphere to change. These include experiments with radiative models of clouds, changes in distribution of particulate matter with height, the effects of CO_2 and other combustion gases, solar constant, volcanic dust, aerosols and atmospheric chemistry. Occasionally experiments are performed in which the physical parameters of a particular latitude strip are taken as the global mean values in order to get a sense of the changes in vertical structure to be expected at different latitudes and in particular to estimate how the structure varies under perturbation.

Much of the mathematical details of the radiative transport calculations of these models can, with some modification, be used in tandem with those models that treat horizontal transport since the radiative part is calculated separately to give heating rates.

D. The Thermodynamic (Adem) Model

The thermodynamic model of Adem is an operating climate model developed on the basis of the assumption that for periods of a month or longer climate can best be described by determining the mean thermal state of the atmosphere. The model uses two basic equations, one for the conservation of thermal energy for the atmospheric layer and one for the conservation of thermal energy for the ocean layer. The two layers are coupled in the full model. In each equation there is a two dimensional horizontal eddy diffusion term (the two dimensional version of the one dimensional transport term in the energy balance equation of section II.B). In addition to the eddy diffusion terms there is a term that parameterizes the transport by the mean winds in the atmospheric equation and a term that parameterizes transport by horizontal currents in the ocean equation. Continents and oceans have appropriate values of the albedo - the fraction of solar energy reflected to space - as functions of position on the globe. The chief effect of the continents is a varying albedo due to changing snow and ice cover. Although an initial input variable, albedo-feedback permits computation of changes in snow cover extent.

At present the model computes thermal and solar radiative absorption for each grid point as a function of time with a computed cloud cover. As with all global models the amount of atmospheric structure required for transport by diffusion and advection need not be the same as for the radiative terms, since the time scale for radiative equilibrium is so much smaller.

E. General Circulation Models (GCM)

General circulation models differ from the previously described models in that they treat horizontal momentum directly. That is, they use the analogue of Newton's second law relating the change in momentum to the applied forces. The atmosphere is broken up into several layers and in each layer there are equations for the energy and the horizontal components of the wind velocity. As with the previous models the radiative transport equations must be solved in order to get the radiative heating or cooling at each layer and at each grid point. In order to follow the horizontal velocity components the GCM requires much shorter time steps than is necessary for the other models. The GCM also differs from the prior models in starting with an initial condition and then integrating forward in time from basic principles. It uses more explicit dynamics and less parameterizations then other types of models.

Compared with GCMs, the thermodynamic model differs significantly in method, purpose and simplicity. The GCM attempts to predict climate from first principles while Adem's model generates climate anomalies based on the use of the stored data fields. These data fields represent analog solutions that contain implicitly whatever scales of motion contribute to climate. The model is limited by the quality and extent of the data fields and related parameterizations. In predicting perturbations from normal climate by the subtraction of computed normal from actual fields, the model avoids common biases or errors that may be introduced by computational schemes and common parameterizations.

III. THE 'GREENHOUSE-EFFECT'

A. Explanation of the Effect

The sun supplies the energy that drives the motions of the atmosphere and oceans. Solar radiation enters the top of the atmosphere with a characteristic spectrum that is mostly in the visible. A fraction of this radiation, called the planetary albedo, is reflected to space. The remainder is absorbed and transformed as it interacts with the earth and reaches equilibrium. The transformed radiation has a characteristic spectrum that is mostly in the infrared. It is referred to variously as long-wave or thermal radiation. The spectra of both incoming solar and outgoing thermal radiation are defined by the equilibrium black body emission function (the Planck formula). This is a strictly thermodynamic relation because radiation and matter come to equilibrium on time scales much shorter than those of the macroscopic motions.

The Planck formula depends on the absolute temperature of the emitting surface and wavelength. The solar radiation, shown in Fig. 1, has the spectrum of an emitting surface with a mean temperature of 6000°K. For contrast the spectrum corresponding to the present mean temperature of the earth of about 288°K appears on the right. Both curves have been normalized relative to their respective maxima so they appear to have the same height. The actual intensity of the solar curve is about four million times that of the thermal curve. Thermal radiation, for temperatures characteristic of the earth and its atmosphere, is predominantly in the range 4 to 40 μm.

As will be seen in Section IV.A where we elaborate on the lowest order radiation balance model, if we assume that the planetary albedo of the earth is 0.30, then the remaining fraction, 0.70, of the solar radiation will be

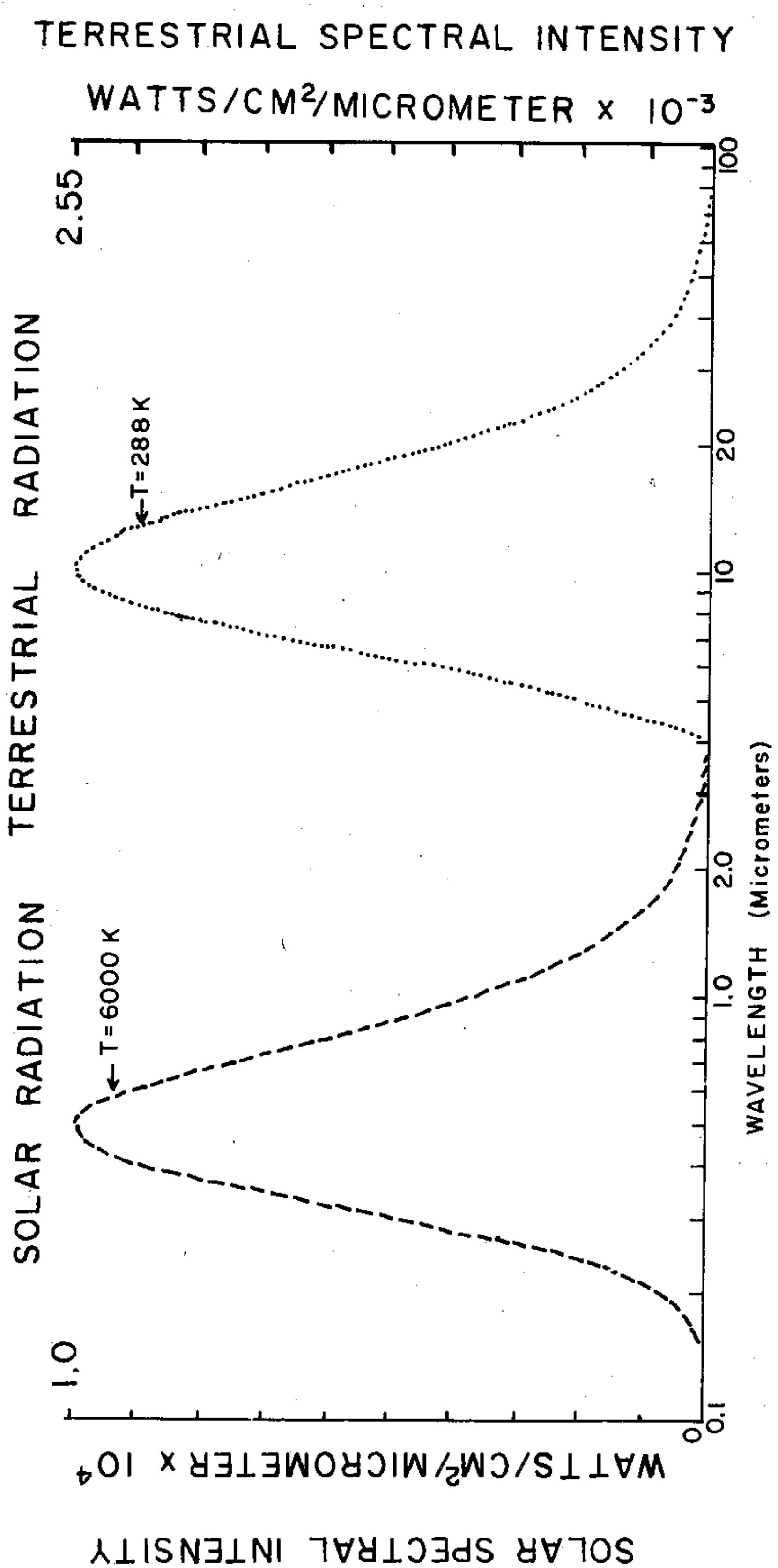


Figure 1. Comparison of solar spectral intensity (left-side scale) with terrestrial spectral intensity (right-side scale).

absorbed and transformed into thermal radiation with a mean temperature of T_e=255°K (or -18°C). T_e is called the effective radiation temperature of the earth. Just as the sun appears to be radiating at the relatively cool effective temperature of its outer layers (6000°K) there appears to be an effective radiating temperature for the earth from its relatively cooler upper troposphere (255°K). The surface temperature of the earth is 288°K. The reason that the surface temperature is warmer is due in part to the presence of the so called greenhouse gases that absorb strongly within the 4 to 40 μm thermal spectrum. Absorbing gases very quickly reradiate the energy they get from the surface of the earth, but in the atmosphere a gas radiates both upward and downward, while the surface merely radiates upward. The spectrum of the equilibrium radiation in the atmosphere will be determined by the actual temperature of the air. It is the mediating effect of the atmospheric absorbers and the fact that they radiate downward as well as upward that provides an additional bath of heat for the surface. This heating is called the "greenhouse effect" simply because the role of the absorbing gases resembles what was once thought to be the role of the glass of the greenhouse in trapping infrared radiation.

A key scientific problem to be solved is the evaluation of the increased greenhouse effect resulting from an increase in combustion gases in the atmosphere.

B. The Greenhouse Gases

The expected role of the greenhouse gases can be illustrated with use of Fig. 2. The figure shows part of the envelope of the thermal emission curve for T = 288°K from 4 to 20 μm. Estimates of the absorption curves of H_2O, CO_2

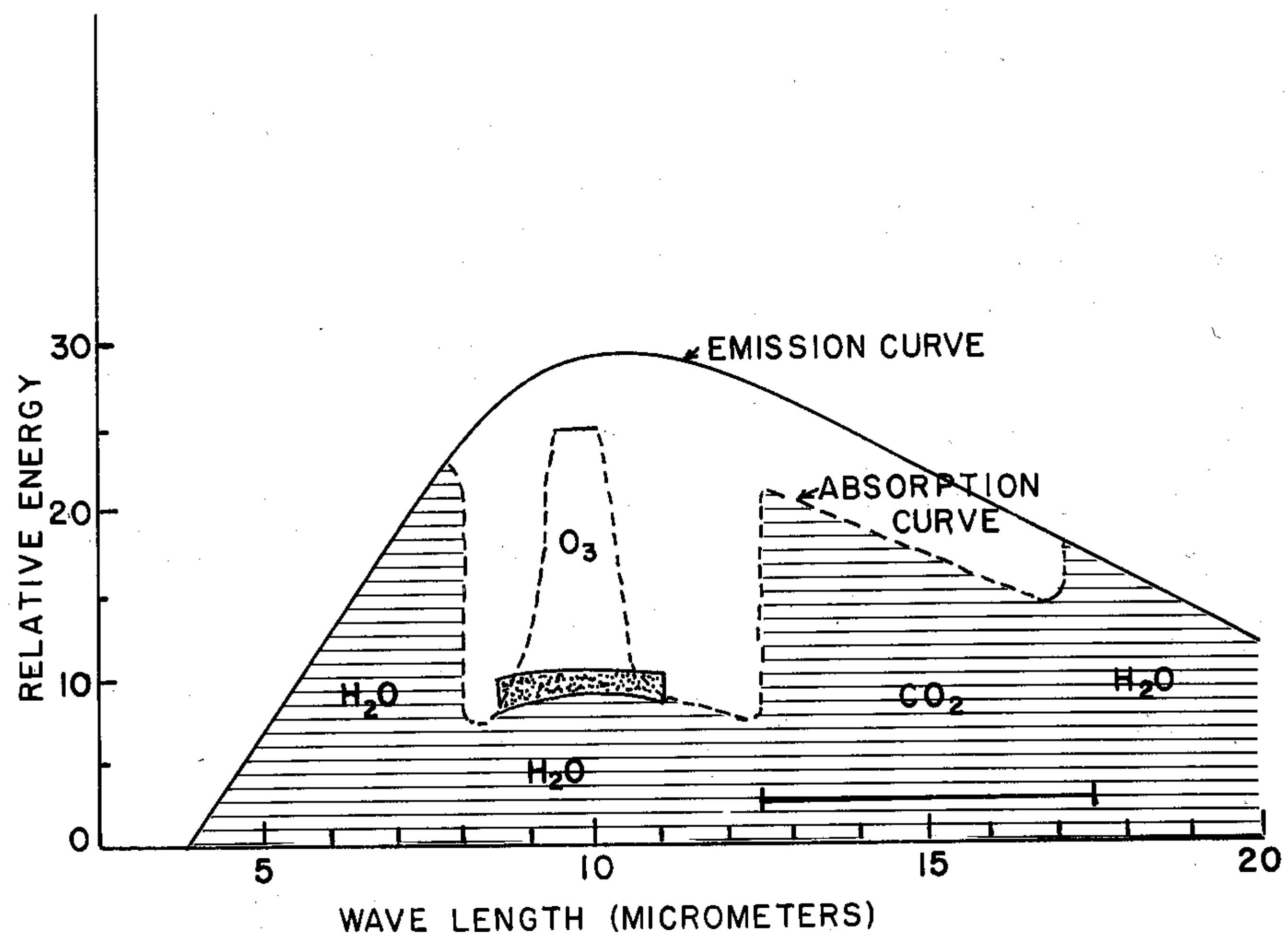


Figure 2. The spectral distribution of emitted and absorbed radiation in the atmosphere. The region of strong absorption by water vapor and CO_2 is horizontally lined. The main CO_2 absorption band is shown by the bracket centered on 15 micrometers. Weak CO_2 absorption is shown by the stippled region.

and O_3, which are sketched from computations based on data in Kondratyev [7] correspond well with a similar figure in Ref. [2]. The horizontally striped region indicates roughly: the main absorption regions of water vapor between 4 μm and 8 μm and above 17 μm; and of CO_2 between 12.5 μm and 17 μm. The principal infrared window to space is between 8 μm and 12 μm. Within the window are an ozone (O_3) absorption band and a relatively unimportant (for present climate) set of CO_2 bands (stippled). If CO_2 were to increase in the atmosphere the principal effect would be a filling in of the presently weak absorption band in the window to space as well as a filling in to the left of the strong absorption band that begins at 12.5 μm. If the CO_2 is more absorbing, it will reradiate more both upward and downward. If all of the other physics remains the same, the effect of this increased downward radiation would be to further increase the temperature of the surface. If the water vapor content were to increase there would be a similar filling in of the window region with more absorbing gases. The other greenhouse gases with absorption bands within the window include NO_x, methane (CH_4), ammonia (NH_3), the halomethanes (freons), carbon monoxide (CO) and hydrocarbons. Moreover, increased emission of NO_x and CO can increase CH_4 and O_3 in the troposphere [8, 9] via chemical reactions that compete with reactions that would otherwise remove them.

Most attention has been directed to the roles of H_2O and CO_2 principally because the data base on them is far more extensive and because the steady increase of CO_2 has been well established while the future increase seems a rational projection.

According to the Jason group [2] the freons have absorbing bands in the middle of the atmospheric window so that if they were to increase by a factor of about one hundred they could contribute strongly to the greenhouse effect.

N_2O, CH_4 and NH_3 appear to be marginally important at present. These gases would fill in the window from the left as CO_2 does from the right if they were to increase. Most recently Lacis et al. [9] calculated that the warming from the increase in trace gases, CH_4, N_2O and chlorofluorocarbons during 1970-1980 amounts to 50% to 100% of that due to CO_2 in the same period. Apparently then, all increases in greenhouse gases plus aerosols should be considered in the total anthropogenic effect.

IV. DESCRIPTION OF THE MODELS

A. Radiation Balance Model

The description and results given here for this most primitive of models follows the standard derivations and results of others, eg Chamberlain [10].

Picture the earth as a uniformly rotating ball with a homogeneous atmosphere in radiative balance with the mean solar heat flux at the top of the atmosphere of S_0 = 1367 watts/meter^2. Moreover, suppose that in equilibrium the earth radiates as a black body at the effective temperature T_e. The sun's radiative flux is plane parallel with a certain fraction, the albedo α, being reflected into space. The amount $\pi R^2\ (1 - \alpha)\ S_0$ is absorbed; πR^2 is the effective area for plane parallel rays striking a spherical earth with radius R. The absorbed energy is reradiated according to the radiation balance equation:

$$\frac{dQ}{dt} = -\epsilon A\sigma\,(T^4 - T_1^4)$$

$$(4\pi R^2)\ \sigma T_e^{\,4} = (\pi R^2)\ (1 - \alpha) S_0, \qquad (1)$$

where the Stefan-Boltzmann constant σ = 0.56687 × 10^{-7} watts/m^2/°K^4. For the value α = 0.3, the effective radiation temperature of the earth T_e = 254.4°K.

A simple relation between surface temperature, T_s and T_e can be derived from the following conditions: the thermal radiation is in local thermodynamic equilibrium with the atmospheric gases; the absorption coefficient is independent of frequency (the grey gas approximation); the atmosphere can be treated in a plane parallel geometry; and the thermal radiation flux goes either vertically up or vertically down. From this it is simple to derive [10] the relation

$$T_s^{\,4} = T_e^{\,4}\ (1 + 0.75\ \tau_g), \qquad (2)$$

where τ_g is the effective optical depth of the atmosphere - a non dimensional measure of the opacity or absorbing capacity of the atmosphere. So far the theory does not give a value for τ_g.

From Eqs. (1) and (2) we get

$$\frac{\sigma T_s^{\,4}}{A_s} = \sigma T_e^{\,4} = \frac{(1 - \alpha)S_0}{4} \qquad (3)$$

where A_s = 1 + 0.75 τ_g.

If, as is the present practice, one assumes that α remains constant if CO_2 is doubled, then T_e remains unchanged. However, τ_g is a measure of absorbing material in the infrared so that τ_g must increase with the CO_2 increase and with it, A_s. The ratio $T_s^{\,4}/A_s$ must remain constant by assumption so that $T_s^{\,4}$ will increase just enough to compensate for the increase in A_s.

A more sophisticated calculation is required to get τ_g. The Jason group [2], in a calculation that summed up the contributions of the absorption coef-

ficients of the major atmospheric constituents found a mean τ_g of 0.748 for the present CO_2 and 0.828 for double CO_2. Substitution of these values gives

$$T_s \text{ (present } CO_2) = 284.9°K$$

and

$$T_s \text{ (double } CO_2) = 287.6°K.$$

The actual values of T_s are not important but any change in T_s is important. The warming is ΔT_s = +2.7°C. In a more complete calculation involving nine absorption bands, the Jason group [2] obtained a 3°C change. The result for a model like this can be only suggestive.

The model producing these results gives the wrong temperature lapse rate for the lower troposphere. The lapse rate is the rate at which temperature falls with altitude. For the case of purely radiative equilibrium, the lapse rate in the lower troposphere will be steep enough for the upper air to be colder and denser than the lower air. Because ~~this~~ is mechanically unstable (a convective instability) the upper air will tend to sink and mix with lower air until the lapse rate reaches a stable value, that is; equal to or less than the adiabatic curves shown in Fig. 3. Because a solution with a stable lapse rate is required for a meaningful result it is necessary to modify the procedure. The simple procedure followed is the replacement of the lower portion of the initially-derived lapse rate curve with one of the adiabatic curves, i.e. the dashed curve of Number 3. The use of such an atmospheric structure would supply enough thermal radiation from the lower troposphere to maintain the radiative profile above the point of intersection C [10]. This

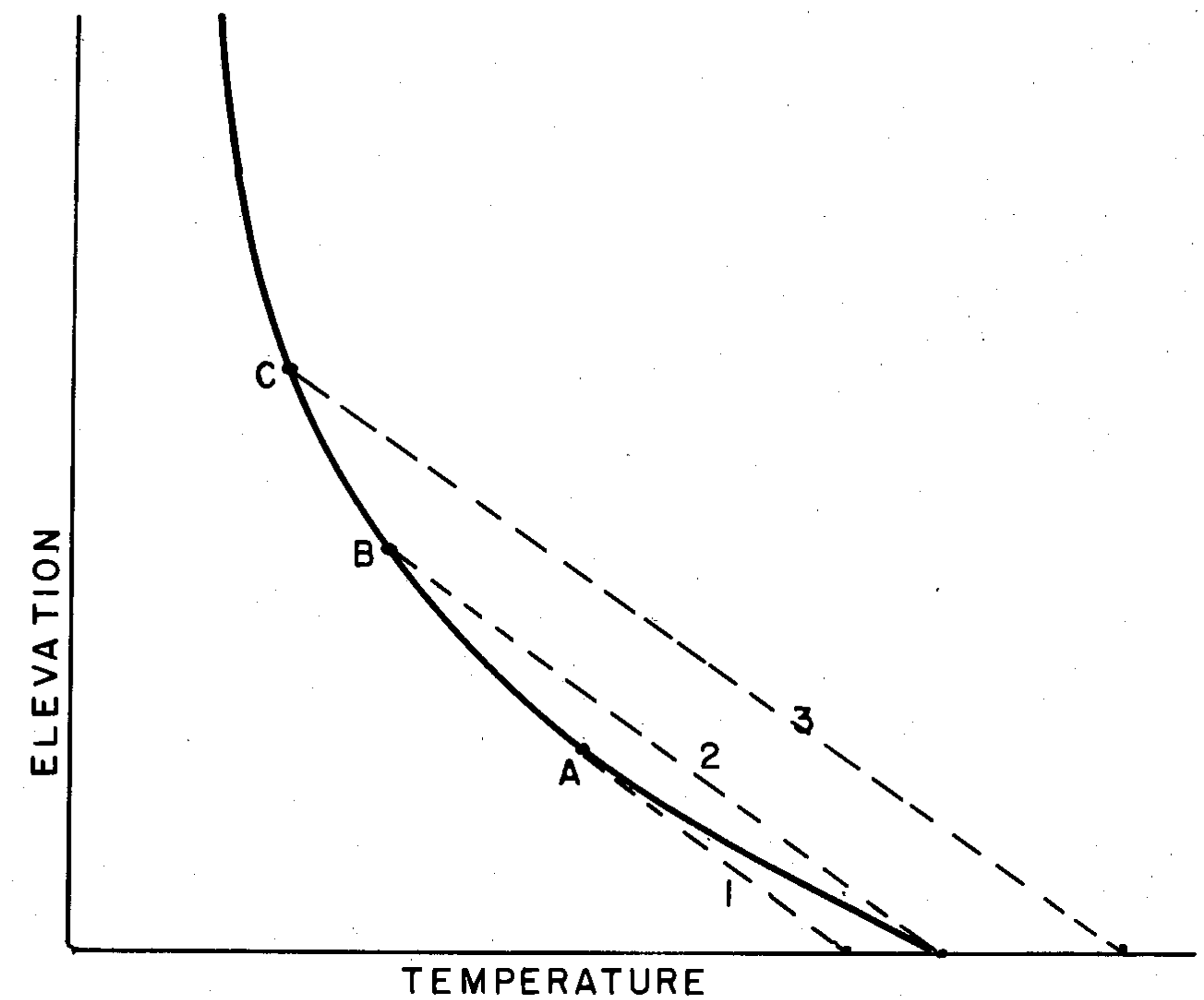


Figure 3. The vertical temperature lapse rate curve resulting from radiation balance solutions (solid curve). Dry adiabatic (constant) lapse rate curves are shown by broken lines 1,2 and 3. Below A the lapse rate curve is unstable. Adiabatic curve 3 is substituted for the lower portion of the lapse rate curve below the point of intersection at C to achieve convective stability and the maintenance of the radiation profile above C.

converts the radiation balance model into the crudest of the radiative-convective models (to be given more attention in Section C).

B. Energy Balance Models

Energy balance models are the next in complexity. They add a latitude dependence and therefore the capacity to treat snow-ice feedback. Moreover, they are capable of analytical solutions limited to highly idealized situations. For these models [11] the globe is divided into latitude strips or zones over which a balance equation states that the solar heat energy flux entering each latitude belt is exactly balanced by the loss rate. In the steady state, the equation for latitude belt i is

$$(\text{net transport out})_i + (\text{infrared out})_i = (\text{solar energy in})_i. \quad (4)$$

Each term would be in units of energy/second/area after the common area of the latitude belt has been divided out. Recall that Eq. (3), the corresponding equation for the radiation balance model has the form

$$(\text{infrared out}) = (\text{solar energy in}).$$

The extra term in (4) represents horizontal transport of heat carried by fluid motions. The properties for each latitude belt are average quantities. The only spatial variable is the quantity $x = \sin\theta$ where θ is the latitude.

In (3) the quantity $\sigma T_s{}^4/(1 + 0.75\tau_g)$ represents the total infrared radiation back to space. One could use such a formula for each strip. However, it is more convenient to convert $T_s = T_s(x)$ to Celsius degrees by $T_s(x) = 273 + T(x)$ where $T(x)$ is in °C and replace the infrared radiation term on the left side of Eq. (3) with the linear version on the left hand side of (5):

$$A(x) + B(x)T(x) = S_0(x)[1 - \alpha(x)]/4 \quad (5)$$

where A and B, in the linearization, absorb the constants of $\sigma T^4/A_s$ but are given experimentally derived values below. $S_0(x)$ is the average value of the solar flux and $\alpha(x)$ the average albedo at altitude x. The variable x is convenient for this work because the differential dx is proportional to the area of the latitude circle. If (5) is multiplied by dx and integrated over latitude the result would be equivalent to (3). Present cloud cover, variation of water vapor content over the globe and the presence of greenhouse gases are accounted for in (5) by writing

$$\begin{aligned} A(x) &= a(x)/(1 + 0.75\tau_g) \\ B(x) &= b(x)/(1 + 0.75\tau_g) \end{aligned} \quad (6)$$

where A(x) and B(x) are deduced from measurements. The Jason group [2] computes τ_g by using the U.S. Standard Atmosphere for 1976 and allowing the assumed structure to radiate to space. They break the thermal region into nine frequency bands, compute the flux for each band separately and then sum them for the total. Thus τ_g accounts for the presence of the greenhouse gases. Then a(x) and b(x) account for variations in cloud cover and water vapor via the measured quantities A(x) and B(x) in (6).

If one assumes that a(x) and b(x) do not change up to a doubling of CO_2 then a computation of τ_g for the case of CO_2 doubled (all other quantities remaining the same) will give a new set of A(x) and B(x) through Eqs. (6).

This approach is not based on solving the equations of radiative transfer hence, again, an estimate for the greenhouse effect rather than a precise number results.

The energy balance equations deal only with the energy content in the total column of atmosphere above the complete latitude strip. These are represented by an average heat capacity multiplied by the surface temperature T(x). Since there are no horizontal velocities in this picture we have to parameterize "net transport out" in terms of T(x) and its derivatives. The parameterization uses the form of molecular diffusion but here the diffusion term has to account for turbulent and eddy transport of heat. For energy balance models the parameterization takes the form of Eq. (7) (or alternate but similar forms)

$$[\text{net transport out}] = -\frac{d}{dx}\left[D(1-x^2)\frac{d}{dx}T(x)\right], \qquad (7)$$

where D, the diffusion coefficient, is at our disposal. It can be a global constant or vary with x or be prescribed in any way that tunes solutions to present climate. At present, whatever method is taken for fixing D, it is kept the same for estimates of doubled CO_2.

In steady state, the full equation has the form

$$-\frac{d}{dx}\left[D(1-x^2)\frac{dT(x)}{dx}\right] + A(x) + B(x)\cdot T(x) = S_0(x)\left[\frac{1-\alpha(x)}{4}\right] \qquad (8)$$

In (8) the surface albedo can be prescribed or it can be written $\alpha(x) = \alpha[x,T(x)]$ in order to account for variations in the ice line if one perturbs the climate. The Jason group [2] uses this parameterization in slightly different notation

$$[1-\alpha(x)] = Z(x)\cdot\begin{cases}0.7 \text{ if } T(x) > -10°C\\ 0.4 \text{ if } T(x) < -10°C\end{cases} \qquad (9)$$

where Z(x) is a correction for variation of zenith angle with x.

Eq. (8) and its time varying counterpart are useful for numerical experimentation. In their most realistic experiment the Jason group finds that by doubling CO_2 an increase of 2.4°C resulted when water vapor increased (constant relative humidity) from the effect of temperature feedback and sea ice was allowed to shrink to zero. High latitudes increased by 7.5°C. The corresponding results from the original Budyko version of this type of model [12] was 3.1°C for the global change and 9°C at high latitudes.

C. Radiative-Convective Models

Manabe and his collaborators [13, 14, 15] developed these models as a prelude to the incorporation of radiative transfer into general circulation models. All of the physical parameters in these models are taken as global averages and all of the computations are in one spatial dimension with variation only in the vertical (z-axis) measured upward from the surface. The equations of radiative transfer can be considered as bookkeeping relations that keep track of the change in radiation intensity I(f) (in watts/meter^2/unit solid angle/unit frequency interval about the frequency f) in some distance dz. They have the form: the change in intensity in distance

dz = - the amount absorbed - the amount scattered out of the beam + the amount scattered into the beam + the amount emitted by matter into the beam. In principle the equations are first solved for each narrow frequency interval df with boundary conditions specified at the top and bottom of the atmosphere: at the top the net upward flux of thermal radiation must equal the net downward flux of solar radiation; at the surface the net upward thermal flux equals the net downward solar flux. To reduce the computational burden [14, 16] the solar and long wave fluxes are given different emphasis. That is, the solar radiation may be absorbed, scattered or reflected but emission is neglected, while the long wavelength thermal radiation may be absorbed or may be emitted but scattering is neglected. Molecular absorption is a process in which the molecules absorb radiation and go into excited energy states; they then reradiate energy in all directions. Quantum mechanics locates the energy levels and thermodynamics shows how the absorption coefficient is broadened by pressure and temperature variations. Further simplifications involve breaking the frequency spectrum into representative bands and computing mean absorption coefficients over each band. This reduces considerably the number of intervals for which the radiative transfer equations need solution.

In radiative-convective models the atmosphere is divided into uniform layers for numerical solution of the radiative transfer equations. Carbon dioxide is treated as uniformly mixed but water vapor and ozone are given vertical distributions appropriate to present mean climate. Clouds strongly influence both solar and thermal fluxes. The distribution of clouds as high, medium and low is generally prescribed according to present climate statistics. Hansen et al. [17], for example, take climatological cloud cover to be 50% with distributions in the fraction: 0.1 for high, 0.1 for medium and 0.3 for low clouds. (Low clouds cool the surface while high clouds warm it.)

Wavelength dependences of cloud and aerosol properties are included in some of the later R-C models [17].

The essential point is that the radiative transport equations are treated with considerable detail in R-C models. At any level they give the net heating or cooling after summing over all frequencies.

In Section IV A we saw that the atmosphere is unstable under purely radiative balance for the very simple model described. To avoid this problem in R-C models another set of conditions is required for stability. There must be some mechanism to transport heat upward from the surface (a convective adjustment) so that a stable temperature lapse rate will exist. One of the several alternative methods for performing these adjustments is via the time-stepping procedure of Refs. [14, 17]. (In this and the more complex models that follow, artificial time steps can be used to go from an initial state to the desired equilibrium state without changing the external conditions or solar forcing.) One begins with a standard atmosphere having a given composition and temperature structure subject to the given incoming solar flux and suitable boundary conditions at the surface. Then the equations of radiative transfer are solved to compute the radiative heating terms at each atmospheric level. Given these, the density of the air, the width of the level, and a suitable time step Δt one can compute ΔT_i the temperature adjustment within the i^{th} level. If the lapse rate exceeds 6.5°C/km -- a standard normal for mid-latitudes used in most R-C models -- the atmosphere is unstable and enough heat (or equivalently a convective adjustment to ΔT) must be added to ensure that the lapse rate will be 6.5°C/km or less. With the new temperature structure the radiative transport equations are solved again subject to the same boundary conditions to get new heating rates. The procedure is iterated until the atmosphere is in radiative and convective balance.

Hansen et al. [17] performed different experiments for doubled CO_2 -- the differences are with cloud parameterization, relative humidity, snow and ice and vegetation albedo feedback. With relative humidity and cloud temperatures fixed at present values and with the 6.5°C/km limiting lapse rate they find that the mean surface warming is ΔT_s = 2.8°C with an uncertainty of a factor of 2. In contrast, Augustsson and Ramanathan [18] give ΔT_s = 2°C for a different cloud parameterization. The quoted numbers are those preferred by the authors of [17] and [18] out of sets of runs with a variety of parameterizations. However, similar assumptions lead to similar results (see table 1 of Ref. [17] and table 2 of Ref. [18] -- a clear indication of the sensitivity of the results to assumptions about the cloud physics.

Hummel and Reck [39] improved on previous radiative-convective models by adding water vapor transport to their version of the early Manabe-Wetherald model thus permitting calculation of cloud location and thickness. Prior models used a constant relative humidity profile and cloud distribution. For a doubled CO_2 content and a standard cloud cover input their modification gives an increase of surface temperature of 2.05° compared with 1.71° for the Manabe-Wetherald model. This difference is due to a larger, more realistic water content.

References [14, 16, 17] give a balanced and clear picture of the techniques of radiative-convective modeling.

D. The Thermodynamic (Adem) Model

The basic assumption of this model is that for periods of a month or longer the mean state of the atmosphere depends primarily on the thermodynamics of the atmosphere and seems to be but weakly dependent on the dynamical

$\frac{dQ}{dt} = -hA(T-T_0)$

motions -- those governed by the fluid dynamics version of Newton's laws. The model follows the time evolution of the thermodynamic state of an atmospheric layer about 10 km high that includes a cloud layer, an ocean layer of 50 to 100 meters in depth and a continental layer of negligible depth and heat storage. It also includes a layer of snow and ice over the continents and oceans. The basic prognostic equations used in this system are those of conservation of thermal energy applied to variables that are time averaged over a prescribed interval. It is assumed that the equations of hydrostatic equilibrium, the perfect gas law, and the continuity equation are valid for the time averaged variables.

The thermal energy equations for atmosphere and oceans are integrated over their respective vertical heights -- about 10 km in the atmosphere and 50 to 100 m in the oceans. The resulting equations follow the mean energy of the atmosphere chosen proportional to the absolute temperature T_m at an altitude equal to one half of the mean height of the atmosphere, and the mean energy of the oceans chosen proportional to their surface temperature T_s.

Three basic equations are used to describe the atmosphere, oceans and continents respectively. For the atmosphere and oceans, the equations (which have the same form and are coupled in a full solution) have terms on the left side for local rate of change of thermal energy, heat transport by eddy diffusion, heat transport by mean winds (currents) and vertical heat transport (below the ocean mixed layer). These are balanced on the right side by the heat sources and sinks: radiation, latent heat and sensible heat. For the continents, which have insignificant storage depth and mobility, the left side terms are zero and only the balance among the heat sources and sinks is considered.

Albedo feedback for snow and ice is obtained by adjusting the snow-ice margin to a selected isotherm (currently 0°C) by iterative solutions until convergence is obtained. All of the terms of the atmosphere-earth radiation balance are also computed internally in the model solutions. Changes in cloud amount are computed as a function of latent heat changes.

Solutions of the linearized differential equations are carried out at 512 grid points over the hemisphere. Output is in the form of hemispheric maps for surface (land and water) and mid-tropospheric temperatures. In addition, all of the diagnostic terms involved are also printed out in separate charts. These include evaporation at the surface, latent heat of condensation in the atmosphere, computed meridional and zonal winds and associated heat transports, absorbed surface radiation, long wave and net radiation and cloud cover.

The model has been applied with success to the calculation of absolute and anomalous values of all of the above terms. It has also been applied with good results to the computation of known long-range climate changes during geologic time.

Although this model was developed primarily for prediction of current climate, it can be modified to be applied to predict the anthropogenic changes in climate for increased combustion gases.

The current model has been used to get a provisional prediction of a doubled CO_2 effect by using published values of the changes that would occur in black-body emission. A mean increase of 0.6°C is predicted in the experiment with a high-latitude change of 2° and a low to mid-latitude change of about 0.5°. These values may be revised when the model is optimized for the experiment.

The mathematical version of the model is given below.

In the present form of the model the equations for T_m (the mid-tropospheric temperature) and T_s (the surface temperature) both have the general form

$$\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T - K\nabla^2 T = \text{heat sources and sinks} \qquad (11)$$

The first term is proportional to the local time rate of change of the energy. The second term represents the transport of heat by mean motions: for the atmosphere $\vec{V}$ is determined by thermodynamic relations -- the geostrophic wind relations -- and for the oceans is determined from the surface wind speeds [19]. The third term represents horizontal diffusion of heat by eddy and turbulent motions. The right hand sides, the heat sources and sinks (HSS) are:

$$\text{HSS for the atmosphere} = E_t + G_5 + G_2, \qquad (12)$$

and

$$\text{HSS for the oceans} = E_s - G_3 - G_2. \qquad (13)$$

In addition, with neglect of heat storage in the continents the third equation reads:

$$0 = E_s - G_3 - G_2 \qquad (14)$$

for the continental surfaces.

In (12) E_t is the heat energy added to the atmosphere by radiation, G_5 is the heat added by condensation of water vapor in the clouds and G_2 is the heat added by vertical turbulent transport from the surface - a parameterization of the convective transport that is dealt with by the convective adjustments in radiative-convective models. In (13) and (14) E_s is the rate at which energy is added to the surface by radiation, and G_3 is the rate at which heat is lost by evaporation.

The parameterization of E_t and E_s is based on assumptions that the cloud layers and the earth radiate as black bodies and that the clear sky atmosphere has a window for wavelengths between 8 μm and 13 μm. They are given in terms of T_s, T_m, the insolation I at the given latitude, the cloud cover, the total radiation received at the surface (for E_s) under clear sky conditions and the surface albedo α. Over the oceans the quantities G_2 and G_3 are parameterized in terms of measured normals, departures of $(T_s - T_m)$ from their normal values and normal surface wind speeds. Over the land G_2 has the same parameterization while G_3 simply depends on empirical normals, and a known function of map coordinates. Similarly, the heat gained by condensation of water vapor in the clouds G_5 is given in terms of its normal seasonal values G_{5N} and $(T_m - T_{mN})$ and its first order derivatives with respect to map coordinates. (The subscript N indicates normal values.)

The cloud cover E is a variable given by:

$$\varepsilon = \varepsilon_N + D_2\,(G_5 - G_{5N}) \qquad (15)$$

where ε_N is the normal cloud cover and D_2 is a constant. Details of the parameterizations are given in Refs. [20, 21, 22, 23].

E. General Circulation Models (GCM)

The design of general circulation models begins with the basic equations governing large scale atmospheric motions and follows by transforming them into some kind of finite differences scheme suitable for solution on digital computers. In this process, the original equations and boundary conditions (or the finite differences scheme itself) would be altered to remove the physical mechanisms responsible for wave motions that would otherwise be generated by errors in initial data. These waves would be spuriously amplified by computational rather than actual physical instabilities and ultimately swamp the motions under study [24].

The first of the basic equations is the equation of conservation of mass. It states that if you follow <u>an individual parcel of gas</u> in time the total mass of the parcel remains constant. This becomes:

The fractional change in density of the parcel with time = the negative of the fractional rate of change of its volume with time... (16)

(Thus a fractional <u>increase</u> in volume of 1% would be accompanied by a fractional <u>decrease</u> in density of 1%.)

The next equation describes the evolution of the internal energy per unit mass e of the parcel in time. In terms of the absolute temperature T and C_v the specific heat at constant volume:

$$e = C_v T \qquad (17)$$

The energy equation (the First Law of Thermodynamics) reads:

The time rate of change of internal energy + the rate of working by the fluid system = the rate at which heat is added to the system. (18)

Equation (8) of the energy balance models is derived as an approximation to Eq. (18). For Adem's model, Eqs. (16) and (18) together with a parameterization of the mean motion reduce to equations (11) and (12) for the atmosphere and (11) and (13) for the oceans.

The new equations for GCM are the fluid dynamical versions of Newton's Second Law F = ma. In cartesian coordinates, for the horizontal west to east coordinate x and velocity u and the south to north coordinate y and velocity v the equations read:

$$\rho \left(\frac{du}{dt} - f\ v\right) = - \frac{\partial p}{\partial x}, \tag{19}$$

and

$$\rho \left(\frac{dv}{dt} + f\ u\right) = - \frac{\partial p}{\partial y}, \tag{20}$$

where the symbol $\frac{d}{dt}$ stands for the time rate of change as we follow the given parcel of fluid, p is the pressure, $\frac{\partial p}{\partial x}$ and $\frac{\partial p}{\partial y}$ are components of the pressure gradient (the force terms), ρ is the density of the parcel, f the Coriolis parameter is equal to $2\Omega \sin\phi$ where Ω is the angular rotation of the earth (2π radians/day) and ϕ is the latitude. Eqs. (19) and (20) when multiplied by the volume of the parcel are in the form of Newton's Law

$$ma = F \tag{21}$$

in a rotating frame.

Vertical accelerations (which would be perturbations on the fundamental hydrostatic pressure balance equation of the atmopshere) are important on smaller space scales than the motions followed in meteorology and must be parameterized in order to include an adequate treatment of convective heat transport from the surface to the atmosphere.

Adem's model uses a thermodynamic parameterization of (19) and (20) by setting the d/dt terms equal to zero and computing u and v from

$$u = - (\rho f)^{-1}\ \partial p/\partial y,\ v = (\rho f)^{-1}\ \partial p/\partial x. \tag{22}$$

These are the geostrophic winds and are used wherever advection terms are used. For large scale motions of the kind used in climate studies this is a reasonable approximation since the geostrophic wind approximates the true horizontal velocity to within about 15% in midlatitudes.

For GCM the full set of equations must be transformed into some version of a finite differences scheme suitable for solution by a digital computer. Typical horizontal grid spacings might range from a 4° × 5° net to an 8° × 10° net. For the vertical structure, 2, 7, 9 or more levels are used. With each choice of net there are wavelengths of motions smaller than the grid spacings that cannot be resolved. Because these subgrid motions are important transport mechanisms for energy and momentum their effects must be parameterized in terms of the grid scale variables and their derivatives.

At present the GCM use oceans without surface currents as sources and sinks of heat. In addition to the convection of moisture and sensible heat

(described above for the thermodynamic model) the GCM must also provide for convection of momentum.

In a survey of this size it is difficult to describe in detail the computational complexities of the major models or the various schemes for parameterization of physical processes that can not be treated directly or simply. It is relevant to note that all of these are active areas of present research and that year by year models undergo modification to accomodate changes in knowledge. Reference [1] contains a summary of predictions of the outcome of CO_2 warmings from two of the principal GCM modeling groups: the group led by Hansen at the Goddard Institute for Space Studies in New York and the group led by Manabe at the Geophysical Fluid Dynamics Laboratory at Princeton, N.J. The global mean warming for the most complete of the two sets of models is 2°C for Manabe et al. and 3.5°C for Hansen et al., quoted in [1]. As might be expected different parameterizations and different feedback mechanisms produce different results within the above range.

In the latest published GCM experiment, Gates et al. [27] used a two layer atmospheric model which included an ocean constrained with prescribed climatological temperature and obtained a global surface air temperature warming of only 0.2°C and a surface warming of only 0.1°C. This low result is primarily a function of the use of a prescribed sea surface temperature.

The magnitudes of the warmings by GCM, as with all models are higher at high latitudes. The maximum value, according to Ref. [1], is between 4°C and 8°C in polar and adjacent regions for the annual mean surface ΔT. All models also indicate increased warming in summer and over land, but the magnitudes differ.

V. ASSESSMENT OF THE MODELS

A. Common Assumptions

In climate modeling certain physical processes must be parameterized in order to make computations tractable on current generation computers. This includes eddy diffusion of heat and momentum, convective transport of heat, moisture and momentum, and the radiative properties of the atmosphere. In many of these parameterizations a particular constant (the parameter) is given a value that tunes the final result to present climate. This is a perfectly respectable procedure and enables one to perform experiments involving small changes in solar constant or some physical input with a reasonable expectation that the constants will remain valid for the altered climate state.

Common practice involves the assumption that present parameterizations will be valid for a doubling of CO_2. Some of these parameterizations have a very strong influence on the outcome of the doubling. One such assumption is that the mean planetary albedo α and consequently T_e, the effective radiation temperature of the earth, remain unchanged. An example of this in the simplest case is seen with equation (3):

$$\sigma T_s{}^4/A_s = \sigma T_e{}^4 = (1 - \alpha)S_0/4, \qquad (3)$$

where $A_s = 1 + 0.75\ \tau_s$. It is clear that depending on whether α goes up or down T_e can be colder or warmer.

Another assumption is that the present mean distribution of relative humidity remains fixed for a CO_2 doubling. Since a CO_2 warming will increase the water vapor content of the atmosphere, if relative humidity remains con-

stant, the greenhouse effect of water vapor in the atmospheric window will result in a strong positive feedback. Thus, the Jason group model [2] predicts an additional warming of about 50% of the bare 2 × CO_2 warming. However, in the complex feedback mechanism, increased CO_2 leads to increased temperature with a consequent increase in evaporation and increased moisture content of the atmosphere. Although this effect leads to a further warming, the probable increase in cloud cover would increase albedo and offset the warming effect [38]. The true effects of all of these sensitive relationships are not yet known.

Wherever the models agree on these two assumptions it is likely that the predicted global warmings will be close simply because the final results are very sensitive to the planetary albedo and the relative humidity. The assumptions serve as constraints and as modeling efforts evolve these constraints will be relaxed.

B. Energy Balance Models

Energy balance models are extremely tractable for both analytical and numerical treatment [11, 2]. With them one can follow the lowest order effects of climate change on the ice line and the latitudinal distribution of a warming. The ice line separates the region of snow and ice where the albedo is high from the region of bare earth where it is low. In these models, the ice line can be made a function of surface temperature and will shift latitudinally with the surface temperature.

The principal difficulties with this class of models are:

i. they define all physical variables over a complete latitude strip so that there is no proper separation of oceans and continents;

ii. they have absolutely no advection parameterization -- an important transport mechanism for mid-latitudes;

iii. they have no hydrological cycle and

iv. any interaction between oceans and air would be too crude to offer any reliable time estimates for a warming.

In summary, the models are extremely useful for preliminary experiments since they are fast and simple but they can give no definitive answer about a climate warming.

C. Radiative-Convective Models

Radiative-convective models are one dimensional representations of the earth's atmosphere with variation possible only in the vertical and in time. They were designed originally as precursors for the incorporation of radiative transfer into GCM but have served for a considerable amount of interesting experimentation.

The principal weakness of these models are:

1. they treat a mean earth;
2. they have no horizontal heat transport and
3. the convective adjustments are very crude mechanisms introduced to maintain mechanical stability of the lower troposphere.

Treatments with horizontal transport and realistic oceans and continents could modify any conclusions drawn from radiative-convective models. Nonetheless, these models can be powerful tools for exploring radiative properties of the atmosphere especially parameterizations of cloud cover and dynamics and the effect of industrial pollutants. The fact of a predicted change will be important rather than the magnitude. For accurate magnitudes the radiative computation package must be appended to models with two dimensional horizontal variation and a realistic geography.

Reck and collaborators have studied the effects of a wide range of industrial pollutants on climate with a version of the Manabe-Wetherald radiative-convective model. These include the effect of aerosols on climate [28, 29, 30] and the effects of the freons on atmospheric surface temperature [31]. These and related numerical experiments and others on CO_2 warmings [16, 32] are suggestive rather than definitive at this time.

D. The Thermodynamic (Adem) Model

The thermodynamic model of Adem is the only operating climate model that gives reasonable forecasts of current temperature anomalies. It has also been used on a quasi-operational basis to predict monthly climate with very good performance and has been successful in simulating past climates related to ice ages and different continental locations [33, 34]. Since early in 1980 it has been generating monthly forecasts with good skill for the northern Hemisphere [35, 36]. Other strong points of the model are:

i. it is fast -- a one month forecast takes about 1 minute on an IBM 360/95;

ii. it is the only existing model with a realistic mean ocean having wind driven currents parameterized in a useful way and

iii. it generates cloud cover, the radiation balance, snow-ice feedback and sea surface temperatures internally.

The weak point of the model is that many of its parameterizations, while adequate for present climate predictions, require adjustment for optimum application of the model to the CO_2 warming problem. As with all models, parameterization of physical processes require better and more fundamental understanding of the role of cloud physics, the distribution of moisture in the atmosphere, and the way subgrid scale motions contribute to time mean motions followed by the equations of motion. Further work is necessary on this model to optimize it for application to the CO_2 problem.

E. General Circulation Models

Despite the fact that General Circulation Models include simultaneously details of those processes that control climate, they may not be, at least at this time, the appropriate vehicles for predicting long term climate change for the following reasons (paraphrased from Refs. [2] and [3]:

i. the computing time for current GCM could take from a half of a year to a full year to calculate a century of climate for a single combination of initial conditions or prescribed external parameters;

ii. in order to be useful for climate studies it may require calculation of statistics from an ensemble of numerical integrations and

iii. it is difficult to track down cause and effect relationships with the many degrees of freedom involved in GCM.

No GCM (as of this writing) can predict present climate or give even a two-week forecast. There is a phenomenon of "intrinsic stochasticity" referred to in Ref. [2] which refers to a kind of internal chaotic motion (not driven by external noise) that occurs even in simple dynamical systems that are deterministic. For certain values of the constants in the equation these systems become extremely sensitive to initial conditions so that closely neighboring initial physical states can evolve into quite different final states. Since GCM have so many constants and adjustable parameters the authors of Ref. [2] expect a good amount of such chaotic behavior.

In addition to these difficulties, it is much more difficult to assess the effects of any input assumptions, including errors, on results of the complex GCM than it is for simpler models. Example of effects already detected in which large changes occur are evident in the change from a swamp ocean (no heat storage) to a mixed-layer (heat storage) ocean in the GCM models of Manabe and Wetherald [37] and Manabe and Stouffer [26]. The warming of 3° in the former case falls to 2° in the latter. And in the case of Gates et al. [27] who used effectively an ocean of infinite heat storage a warming of only 0.1° resulted. These are gross effects. Changes due to the many more subtle aspects are much more difficult to trace.

Both Ref. [2] and [3] suggest that simpler models would be more tractable and useful for probing long term variations in climate.

F. Future Directions

Most models prescribe the data for the radiation balance at the top of the atmosphere. Involved with this is the tuning to present conditions of cloud cover, relative humidity and planetary albedo. These terms have a profound influence on the warming due to a change in combustion gas input. It is essential that these terms evolve in some parameterized way, with changing climate. In this connection we note that Ohring and Clapp [38] deduced from observations that the net albedo cooling effect of clouds is slightly greater than the greenhouse warming effect.

In addition to the problems connected with the meteorological parameters, a basic problem appears to exist in the computation of heating rates. This computation requires the solution of the equations of radiative transfer, a process which currently uses in part, analytical expressions devised prior to the advent of present high-speed computers. The magnitude of potential errors in the above procedure should be evaluated and computational strategies devised to determine transmission in sufficiently small frequency bands over the spectrum of interest.

In addition to the above fundamental areas, necessary improvement must still be carried out for many of the parameterizations of both atmospheric and ocean terms.

Despite all of the uncertainties in the classes of models described, their very errors serve to give outside limits of global warming of 0.1°C to 3.5°C from a doubling of CO_2. Effects of trace gases, referred to earlier, might lead to a near doubling of these numbers.

References

1. Ad Hoc Study Group on Carbon Dioxide and Climate (Jule G. Charney, Chm.), "Carbon Dioxide and Climate: A Scientific Assessment," Climate Research Board, National Research Council, Washington, D.C. (1979).

2. G. MacDonald, Chm., et al., "The Long Term Impacts of Increasing Atmospheric Carbon Dioxide Levels," Jason Technical Report JSR-79-04, SRI International, Arlington, Virginia (1980).

3. Schneider, Stephen H. and Robert E. Dickinson, Climate Modeling, Rev. Geophys. and Space Phys., 12, 447-493 (1974).

4. Idso, S. B., Science, 207, 1462 (1980).

5. Newell, R. E. and T. G. Dopplick, Questions Concerning the Possible Influence of Anthropogenic CO_2 on Atmospheric Temperature, J. Appl. Meteorol., 18, 822 (1979).

6. Abarbanel, H., J. Chamberlain, H. Foley, G. MacDonald, W. Nierenberg, M. Ruderman, "The Carbon Dioxide Problem: DOE Program and a General Assessment," Jason Technical Report JSR-80-06, SRI International, Arlington, Virginia (1980).

7. Kondratyev, K. Ya., "Radiation in the Atmosphere," International Geophysics Series, vol. 12, Academic Press, New York (1969).

8. Hameed, Sultan, Robert D. Cess, and Joseph S. Hogan, Response of the Global Climate to Changes in Atmospheric Chemical Composition due to Fossil Fuel Burning, J. Geophys. Res., 85, 7537-7545 (1980).

9. Lacis, A., J. Hansen, P. Lee, T. Mitchell, S. Lebedoff, Greenhouse Effect of Trace Gases, 1970-1980, Geophys. Res. Lett., 8, 1035-1038 (1981).

10. Chamberlain, Joseph W., "Theory of Planetary Atmospheres. An Introduction to Their Physics and Chemistry," International Geophysics Series, vol. 22, Academic Press, New York (1978).

11. North, Gerald R., Robert F. Cahalan and James A. Coakley, Jr., Energy Balance Climate Models, Rev. Geophys. Space Phys., 19, 91-121 (1981).

12. Budyko, M., The Heat Balance of the Earth, Chap. V, in "Climate Change," Cambridge University Press (1978).

13. Manabe, Syukuro and Fritz Möller, On the Radiative Equilibrium and Heat Balance of the Atmosphere, Mon. Wea. Rev., 89, 503-532 (1961).

14. Manabe, Syukuro and Robert F. Strickler, Thermal Equilibrium of the Atmosphere with a Convective Adjustment, J. Atmos. Sci., 21, 361-385 (1964).

15. Manabe, Syukuro and Richard T. Wetherald, Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity, J. Atmos. Sci., 24, 241-259 (1967).

16. Ramanathan, V. and J. A. Coakley, Jr., Climate Modeling Through Radiative-Convective Models, Rev. Geophys. Space Phys., 16, 465-489 (1981).

17. J. Hansen et al., Climate Impact of Increasing Atmospheric Carbon Dioxide, Science, 213, 957-966 (1981).

18. Augustsson, T. and V. Ramanathan, A Radiative-Convective Model Study of the CO_2 Climate Problem, J. Atmos. Sci., 34, 448-451 (1977).

19. Adem, Julian, On the Prediction of Mean Monthly Ocean Temperatures, Tellus, XXII, 410-430 (1970).

20. Clapp, Philip F., S. H. Scolnik, R. E. Taubensee and F. J. Winninghoff, "Parameterization of Certain Atmospheric Heat Sources and Sinks for use in a Numerical Model for Monthly and Seasonal Forecasting." Unpublished Study of Extended Forecast Division, U.S. Weather Bureau, Washington, D.C.

21. Adem, Julian, Experiments Aiming at Monthly and Seasonal Numerical Weather Prediction, Mon. Wea. Rev., 93, 495-503 (1965).

22. Adem, Julian, On the Theory of the General Circulation of the Atmosphere, Tellus, XIV, 102-115 (1962).

23. Adem, Julian, Incorporation of Advection of Heat by Mean Winds and by Ocean Currents in a Thermodynamic Model for Long-Range Weather Prediction, Mon. Wea. Rev., 98, 776-786 (1970).

24. Holton, James R., "An Introduction to Dynamic Meteorology," Second Edition, International Geophysics Series, vol. 23, Academic Press, New York (1979).

25. Goddard Institute for Space Studies, "Proposal for Research in Global Carbon Dioxide Source/Sink Budget and Climate Effects," Goddard Institute for Space Studies, 2880 Broadway, New York, N.Y. 10025 (1978).

26. Manabe, Syukuro and Ronald J. Stouffer, Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere, J. Geophys. Res., 85, 5529-5554 (1980).

27. Gates, W. L., K. H. Cook, and M. E. Schlesinger, Preliminary Analysis of Experiments on the Climatic Effects of Increased CO_2 with an Atmospheric General Circulation Model and a Climatological Ocean, J. Geophys. Res., 86, 6385-6393 (1981).

28. Reck, Ruth A., Atmospheric Temperature Calculated for Ozone Depletions, Science, 263, 116-117 (1976).

29. Reck, Ruth A., Thermal Effects of Stratospheric Ozone Depletion at 85°N Latitude as Influenced by Airborne Particles, Geophys. Res. Lett., 5, 361-364 (1978).

30. Reck, Ruth A., Aerosols in the Atmosphere: Calculation of the Critical Absorption/Back Scatter Ratio, Science, 186, 1034-1036 (1974).

31. Reck, Ruth A., and David L. Fry, The Direct Effects of Chlorofluoromethanes on the Atmospheric Surface Temperature, Atmosph. Environ., 12, 2501-2503 (1978).

32. Ackerman, Thomas P., On the Effect of CO_2 on Atmospheric Heating Rates, Tellus, XXXI, 115-123 (1979).

33. Donn, W. and D. Shaw, Model of Climate Evolution Based on Continental Drift and Popular Wandering, Geol. Soc. Am. Bull., 88, 390-396 (1977).

34. Adem, J., Numerical Experiments on Ice Age Climate, J. Geophys. Res., (in press).

35. Adem, J. and W. Donn, "Comparison of the Earth-Atmosphere Radiation Budget and Albedo Determinations by a Climate Model and by Satellite Observations," in Proc. Fifth Climate Diagnostics Workshop, NOAA, 319-327 (1981).

36. Adem, J. and W. Donn, Monthly Climate Prediciton with a Physical Model, Bull. Amer. Meteorol. Soc. (in press, Dec. 1981).

37. Manabe, Syukuro and Richard T. Wetherald, On the Effects of Doubling the CO_2 Concentration on the Climate of General Circulation Model, J. Atmos. Sci., 32, 3-15 (1975).

38. Ohring, George and Philip Clapp, The Effect of Changes in Cloud Amount on the Net Radiation at the Top of the Atmosphere, J. Atmos. Sci., 37, 447-454 (1980).

39. Hummel, J. and R. Reck, Carbon Dioxide and Climate: The Effects of Water Transport in Radiative-Convective Models, J. Geophys. Res., 86, 12,035-12,038.

2400—5/82—5C

American Petroleum Institute
2101 L Street, Northwest
Washington, D.C. 20037

EXHIBIT 21

EXXON RESEARCH AND ENGINEERING COMPANY
P.O. BOX 101, FLORHAM PARK, NEW JERSEY 07932

M. B. GLASER
Manager
Environmental Affairs Programs

Cable: ENGREXXON, N.Y.

November 12, 1982

CO_2 "Greenhouse" Effect

82EAP 266

TO: See Distribution List Attached

Attached for your information and guidance is briefing material on the CO_2 "Greenhouse" Effect which is receiving increased attention in both the scientific and popular press as an emerging environmental issue. A brief summary is provided along with a more detailed technical review prepared by CPPD.

The material has been given wide circulation to Exxon management and is intended to familiarize Exxon personnel with the subject. It may be used as a basis for discussing the issue with outsiders as may be appropriate. However, it should be restricted to Exxon personnel and not distributed externally.

Very truly yours,

M. B. Glaser

M. B. GLASER

MBG:rva

Attachments

H. N. WEINBERG
NOV 15 1982

Distribution List:

R. W. Cohen
M. J. Connor, Jr.
E. E. David, Jr.
C. M. Eidt, Jr.
W. R. Epperly
R. L. Hirsch
T. G. Kaufmann
D. G. Levine
G. H. Long
J. R. Riley
H. R. Savage
A. Schriesheim
J. F. Taylor
D. T. Wade
H. N. Weinberg

SUMMARY

Atmospheric monitoring programs show the level of carbon dioxide in the atmosphere has increased about 8% over the last twenty-five years and now stands at about 340 ppm. This observed increase is believed to be the continuation of a trend which began in the middle of the last century with the start of the Industrial Revolution. Fossil fuel combustion and the clearing of virgin forests (deforestation) are believed to be the primary anthropogenic contributors although the relative contribution of each is uncertain.

The carbon dioxide content of the atmosphere is of concern since it can affect global climate. Carbon dioxide and other trace gases contained in the atmosphere such as water vapor, ozone, methane, carbon monoxide, oxides of nitrogen, etc. absorb part of the infrared rays reradiated by the earth. This increase in absorbed energy warms the atmosphere inducing warming at the earth's surface. This phenomenon is referred to as the "greenhouse effect".

Predictions of the climatological impact of a carbon dioxide induced "greenhouse effect" draw upon various mathematical models to gauge the temperature increase. The scientific community generally discusses the impact in terms of doubling of the current carbon dioxide content in order to get beyond the noise level of the data. We estimate doubling could occur around the year 2090 based upon fossil fuel requirements projected in Exxon's long range energy outlook. The question of which predictions and which models best simulate a carbon dioxide induced climate change is still being debated by the scientific community. Our best estimate is that doubling of the current concentration could increase average global temperature by about 1.3° to 3.1°C. The increase would not be uniform over the earth's surface with the polar caps likely to see temperature increases on the order of 10°C and the equator little, if any, increase.

Considerable uncertainty also surrounds the possible impact on society of such a warming trend, should it occur. At the low end of the predicted temperature range there could be some impact on agricultural growth and rainfall patterns which could be beneficial in some regions and detrimental in others. At the high end, some scientists suggest there could be considerable adverse impact including the flooding of some coastal land masses as a result of a rise in sea level due to melting of the Antarctic ice sheet. Such an effect would not take place until centuries after a 3°C global average temperature increase actually occurred.

There is currently no unambiguous scientific evidence that the earth is warming. If the earth is on a warming trend, we're not likely to detect it before 1995. This is about the earliest projection of when the temperature

might rise the 0.5° needed to get beyond the range of normal temperature fluctuations. On the other hand, if climate modeling uncertainties have exaggerated the temperature rise, it is possible that a carbon dioxide induced "greenhouse effect" may not be detected until 2020 at the earliest.

The "greenhouse effect" is not likely to cause substantial climatic changes until the average global temperature rises at least 1°C above today's levels. This could occur in the second to third quarter of the next century. However, there is concern among some scientific groups that once the effects are measurable, they might not be reversible and little could be done to correct the situation in the short term. Therefore, a number of environmental groups are calling for action now to prevent an undesirable future situation from developing.

Mitigation of the "greenhouse effect" would require major reductions in fossil fuel combustion. Shifting between fossil fuels is not a feasible alternative because of limited long-term supply availability for certain fuels although oil does produce about 18% less carbon dioxide per Btu of heat released than coal, and gas about 32% less than oil. The energy outlook suggests synthetic fuels will have a negligible impact at least through the mid 21st century contributing less than 10% of the total carbon dioxide released from fossil fuel combustion by the year 2050. This low level includes the expected contribution from carbonate decomposition which occurs during shale oil recovery and assumes essentially no efficiency improvements in synthetic fuels processes above those currently achievable.

Overall, the current outlook suggests potentially serious climate problems are not likely to occur until the late 21st century or perhaps beyond at projected energy demand rates. This should provide time to resolve uncertainties regarding the overall carbon cycle and the contribution of fossil fuel combustion as well as the role of the oceans as a reservoir for both heat and carbon dioxide. It should also allow time to better define the effect of carbon dioxide and other infrared absorbing gases on surface climate. Making significant changes in energy consumption patterns now to deal with this potential problem amid all the scientific uncertainties would be premature in view of the severe impact such moves could have on the world's economies and societies.

PROPRIETARY INFORMATION

FOR AUTHORIZED COMPANY USE ONLY

CO_2 GREENHOUSE EFFECT

A TECHNICAL REVIEW

PREPARED BY THE

COORDINATION AND PLANNING DIVISION

EXXON RESEARCH AND ENGINEERING COMPANY

APRIL 1, 1982

EC-11-5/A2

CO_2 GREENHOUSE EFFECT

A TECHNICAL REVIEW

TABLE OF CONTENTS

CO_2 GREENHOUSE EFFECT

Background

The buildup of CO_2 in the atmosphere has been monitored continuously at the National Oceanic and Atmospheric Administration's (NOAA) Observatory at Mauna Loa, Hawaii, and periodically in other places since 1957. In addition to observing a trend between 1957-1979 that showed atmospheric CO_2 increasing from 315 to 337 ppm, Keeling and others also observed a seasonal variability ranging from 6 to 10 ppm between a low at the end of the summer growing season (due to photosynthesis) and a high at the end of winter (due to fossil fuel burning for heat, and biomass decay). There is little doubt that these observations indicate a growth of atmospheric CO_2 (see Figure 1). It is also believed that the growth of atmospheric CO_2 has been occurring since the middle of the past century, i.e., coincident with the start of the Industrial Revolution. There is, however, great uncertainty as to whether the atmospheric CO_2 concentration prior to the Industrial Revolution (ca., 1850) was 290-300 ppm which one would arrive at by assuming atmospheric CO_2 growth is due to fossil fuel burning and cement manufacturing, or 260-270 ppm based on carbon isotope measurements in tree rings. The information on CO_2 concentration prior to 1850 is important because it would help establish the validity of climatic predictions with respect to the inception of a CO_2 induced "greenhouse effect".

The "greenhouse effect" refers to the absorbtion by CO_2 and other trace gases contained in the atmosphere (such as water vapor, ozone, carbon monoxide, oxides of nitrogen, freons, and methane) of part of the infrared radiation which is reradiated by the earth. An increase in absorbed energy via this route would warm the earth's surface causing changes in climate affecting atmospheric and ocean temperatures, rainfall patterns, soil moisture, and over centuries potentially melting the polar ice caps.

Sources and Disposition of Atmospheric Carbon Dioxide - The Carbon Cycle

The relative contributions of biomass oxidation (mainly due to deforestation) and fossil fuel combustion to the observed atmospheric CO_2 increase are not known. There are fairly good indications that the annual growth of atmospheric CO_2 is on the order of 2.5 to 3.0 Gt/a* of carbon and the net quantity of carbon absorbed by the ocean is similarly 2.5 to 3 Gt/a. Thus, these two sinks (atmosphere and ocean) can account for the total fossil carbon burned (including 0.3 GtC/a** from cement manufacturing) which is on the order of 5-6 Gt/a and does not allow much room for a net contribution of biomass

* Gt/a = gigatons per annum = 10^9 metric tons per year.
** GtC/a = gigatons carbon per annum = 10^9 metric tons of carbon per year.

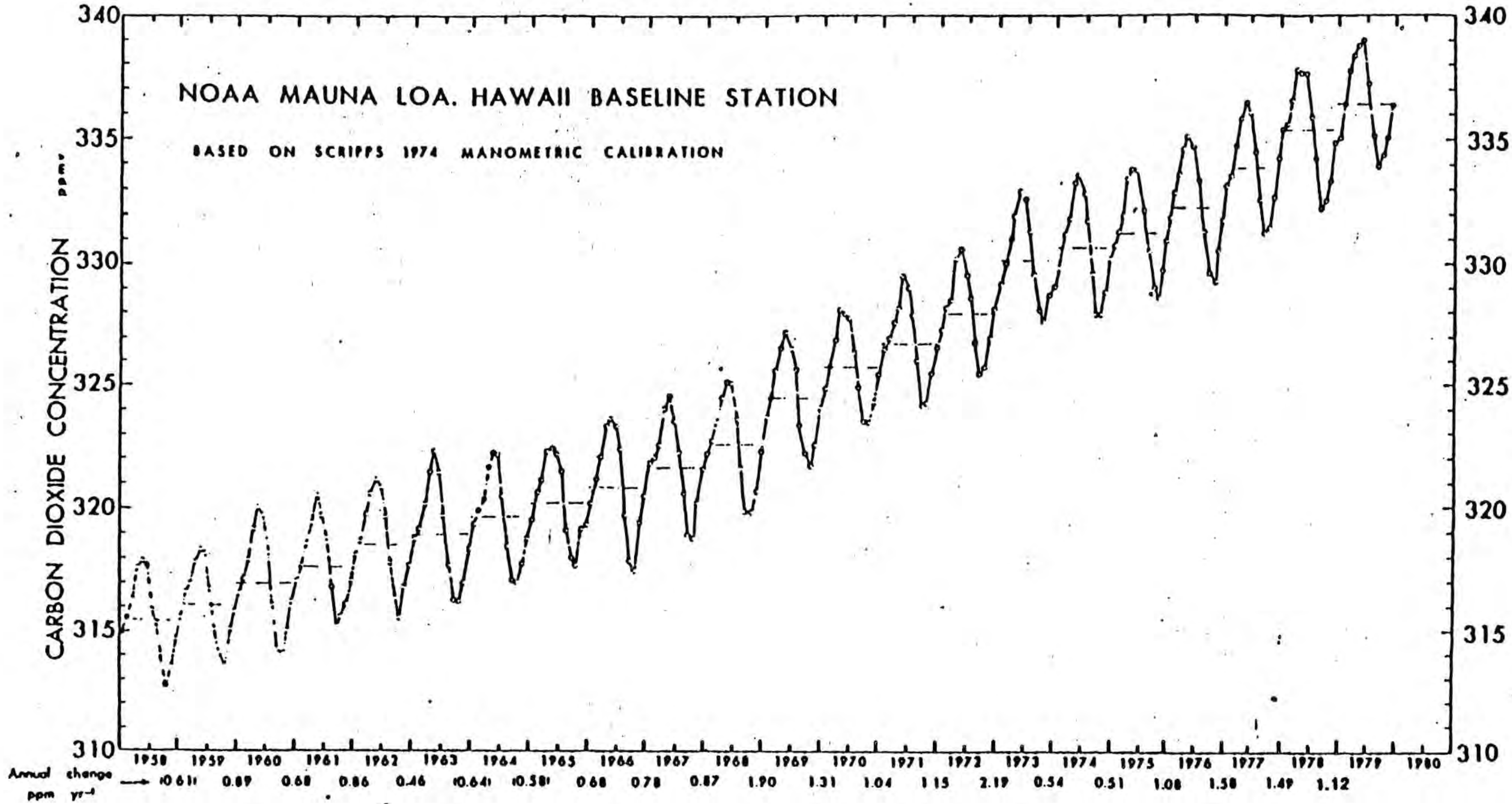


Figure 1 Modern record of atmospheric CO_2 concentrations. Mean monthly concentration measurements at Mauna Loa, Hawaii. Annual changes in parentheses are based on incomplete records; the solid dots are interpolated values (source: NOAA).

carbon. Yet, highly respected scientists such as Woodwell, Bolin and others have postulated a net biomass contribution to atmospheric CO_2 that ranges from 1 to perhaps 8 Gt/a of carbon. During 1980, a number of different groups produced new estimates of the contribution of organic terrestial fluxes to atmospheric CO_2. A consensus has not been reached, but estimates of the net annual terrestial biosphere emissions to the atmosphere now range between a 4 GtC/a source and a 2 GtC/a sink. Figure 2 summarizes the fluxes and reservoirs for the carbon cycle. It should be noted that the net biosphere contribution was assumed to be 0-2 GtC/a.

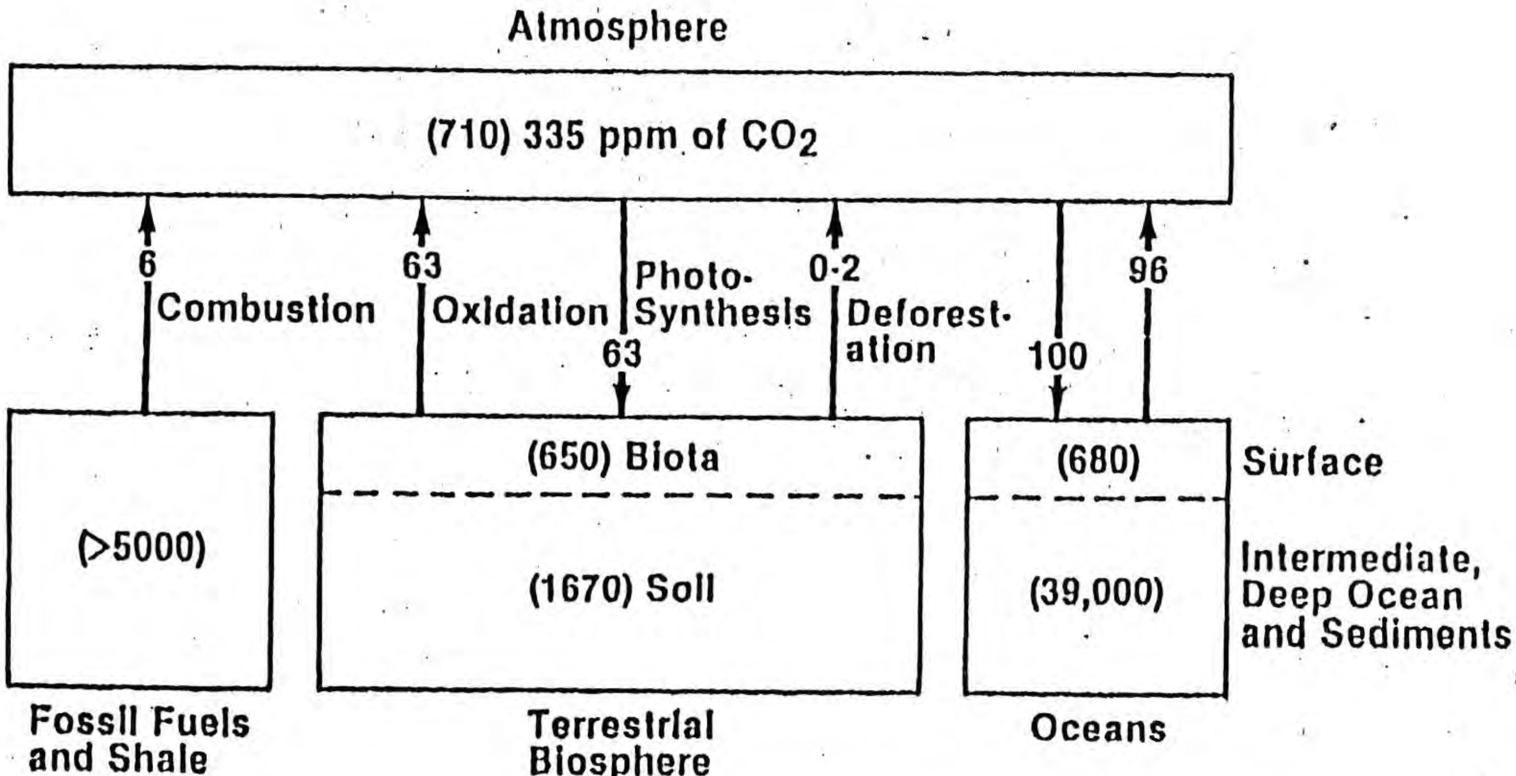
The rate of forest clearing has been estimated at 0.5% to 1.5% per year of the existing area. Forests occupy about 50 x $10^6 km^2$ out of about 150 x $10^6 km^2$ of continental land, and store about 650 Gt of carbon. One can easily see that if 0.5% of the world's forests are cleared per year, this could contribute about 3.0 Gt/a of carbon to the atmosphere. Even if reforestation were contributing significantly to balancing the CO_2 from deforestation, the total carbon stored in new trees tends to be only a small fraction of the net carbon emitted. It should be noted, however, that the rate of forest clearing and reforestation are not known accurately at this time. If deforestation is indeed contributing to atmospheric CO_2, then another sink for carbon must be found, and the impact of fossil fuel must be considered in the context of such a sink.

The magnitude of the carbon fluxes shown in Figure 2 between the atmosphere and the terrestial biosphere, and the atmosphere and the oceans are not precisely known. The flow of carbon between these reservoir pairs is generally assumed to have been in equilibrium prior to the Industrial Revolution. However, the errors in the estimated magnitude of these major fluxes are probably larger than the magnitude of the estimated man-made carbon fluxes, i.e., fossil fuels and deforestation. The man-made fluxes are assumed to be the only ones that have disturbed the equilibrium that is believed to have existed before the Industrial Revolution, and they can be estimated independently of the major fluxes. The man-made carbon fluxes are balanced in Figure 2 between the known growth rate of atmospheric carbon and the oceans. The carbon flux to the atmosphere is 6Gt/a from fossil fuels and cement manufacturing (cement manufacturing contributes about 4% of non-biosphere anthropogenic carbon) and 2Gt/a from deforestation, while 4Gt/a return to the ocean, resulting in a 50% carbon retention rate in the atmosphere. One cannot rule out, in view of the inherent uncertainty of the major fluxes, that the biosphere may be a net sink and the oceans may absorb much less of the man-made CO_2.

Projections of scientists active in the area indicate that the contribution of deforestation, which may have been substantial in the past, will diminish in comparison to the expected rate of fossil fuel combustion in the future. A few years ago a number of scientists hypothesized that a doubling of the amount of carbon dioxide in the atmosphere could occur as early as 2035. This hypothesis is generally not acceptable anymore because of the global curtailment of fossil fuel usage. Calculations recently completed at Exxon Research

FIGURE 2

Exchangeable Carbon Reservoirs and Fluxes



( ) = Size of Carbon Reservoirs in Billions of Metric Tons of Carbon

Fluxes (arrows) = Exchange of Carbon Between Reservoirs in Billions of Metric Tons of Carbon per Year

and Engineering Company using the energy projections from the Corporate Planning Department's 21st Century Study*, indicate that a doubling of the 1979 atmospheric CO_2 concentration could occur at about 2090. If synthetic fuels are not developed and fossil fuel needs are met by new gas and petroleum discoveries, then the atmospheric CO_2 doubling time would be delayed by about 5 years to the late 2090's. Figure 3 summarizes the projected growth of atmospheric CO_2 concentration based on the Exxon 21st Century Study-High Growth scenario, as well as an estimate of the average global temperature increase which might then occur above the current temperature. It is now clear that the doubling time will occur much later in the future than previously postulated because of the decreasing rate of fossil fuel usage due to lower demand.

Description of Potential Impact on Weather, Climate, and Land Availability

The most widely accepted calculations carried on thus far on the potential impact on climate of doubling the carbon dioxide content of the atmosphere use general circulation models (GCM). These models indicate that an increase in global average temperature of $3^{\circ} \pm 1.5^{\circ}C$ is most likely. Such changes in temperature are expected to occur with uneven geographic distribution with greater warming occurring at the higher latitudes, i.e., the polar regions. This is due to increased absorption of solar radiation energy on the darker polar surfaces that would become exposed when ice and snow cover melt due to increasing temperature (see Figure 4). There have been other calculations using radiative convective models and energy balance models which project average temperature increases on the order of $0.75^{\circ}C$ for a doubling of CO_2. These calculations are compared in Figure 5. Figure 6 summarizes possible temperature increases due to various changes in atmospheric CO_2 concentration.

If the atmospheric CO_2 content had been 295 ppm prior to the Industrial Revolution, and an average global temperature increase above climate noise is detectable at the present time, this would add credibility to the general circulation models. However, if the CO_2 concentration and been 265 ppm prior to the Industrial Revolution, then detecting a temperature effect of $0.5^{\circ}C$ now would imply that the temperature for a doubling of CO_2 would be $1.9^{\circ}C$. The projected temperatures for both alternatives fall within the $3^{\circ} \pm 1.5^{\circ}C$ range. Temperature projections for alternate scenarios will be discussed later.

Climate modeling was studied by a committee of the National Research Council, chaired by Jules G. Charney of MIT, and the conclusions are summarized in

* The "21st Century Study" referred to here and in other places in this report has been superseded by a new energy study called the "2030 Study". The new study projects energy demands that are lower than the earlier figures, but not sufficiently different to change any of the conclusions of this report.

Figure 3

GROWTH OF ATMOSPHERIC CO_2 AND AVERAGE GLOBAL TEMPERATURE INCREASE AS A FUNCTION OF TIME

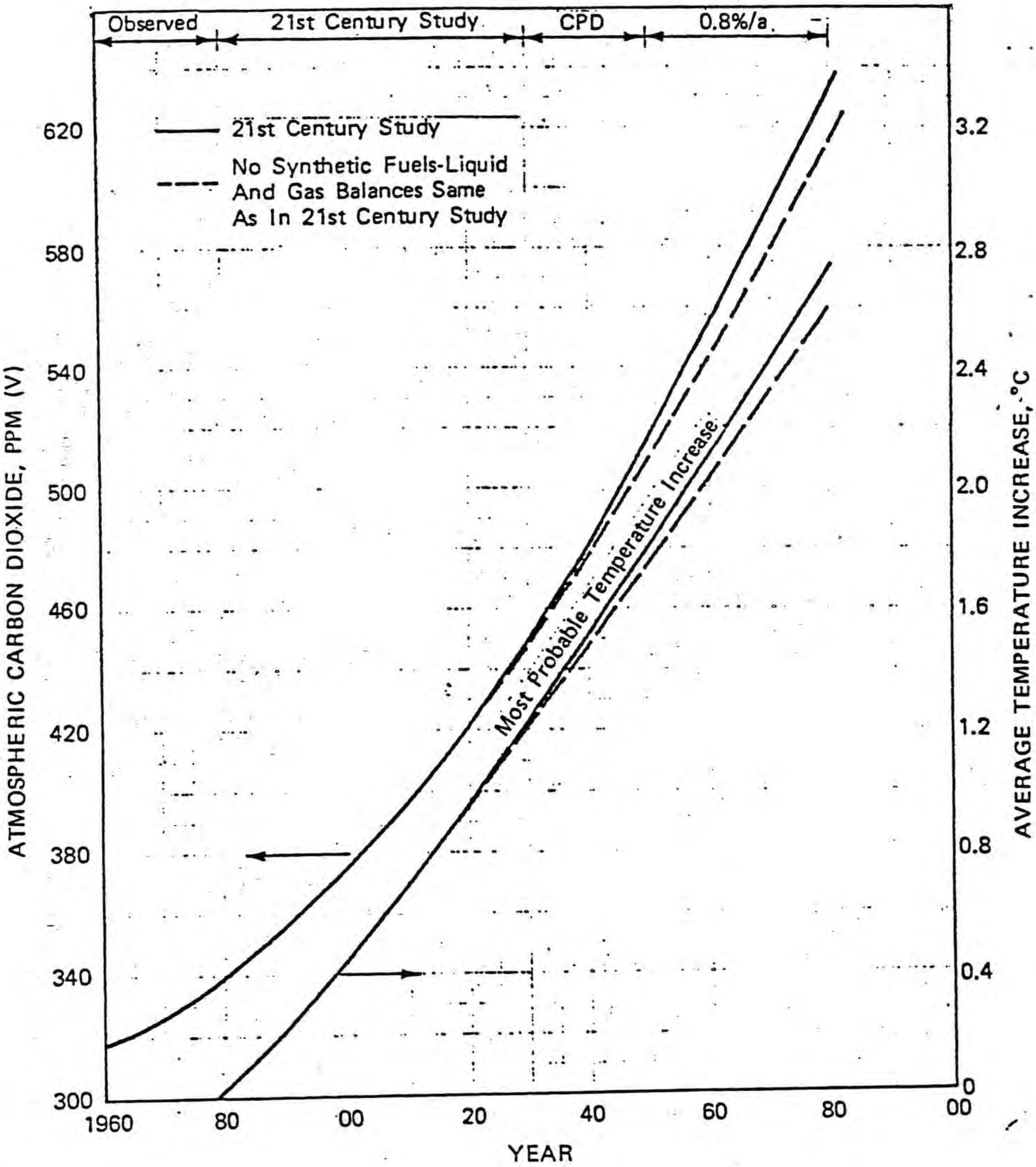


Figure 4

Temperature Change (^oC) Due to Doubling CO_2 Concentrations

Basis: Computed by the U.S. National Oceanic and Atmospheric Administration using their general circulation model.

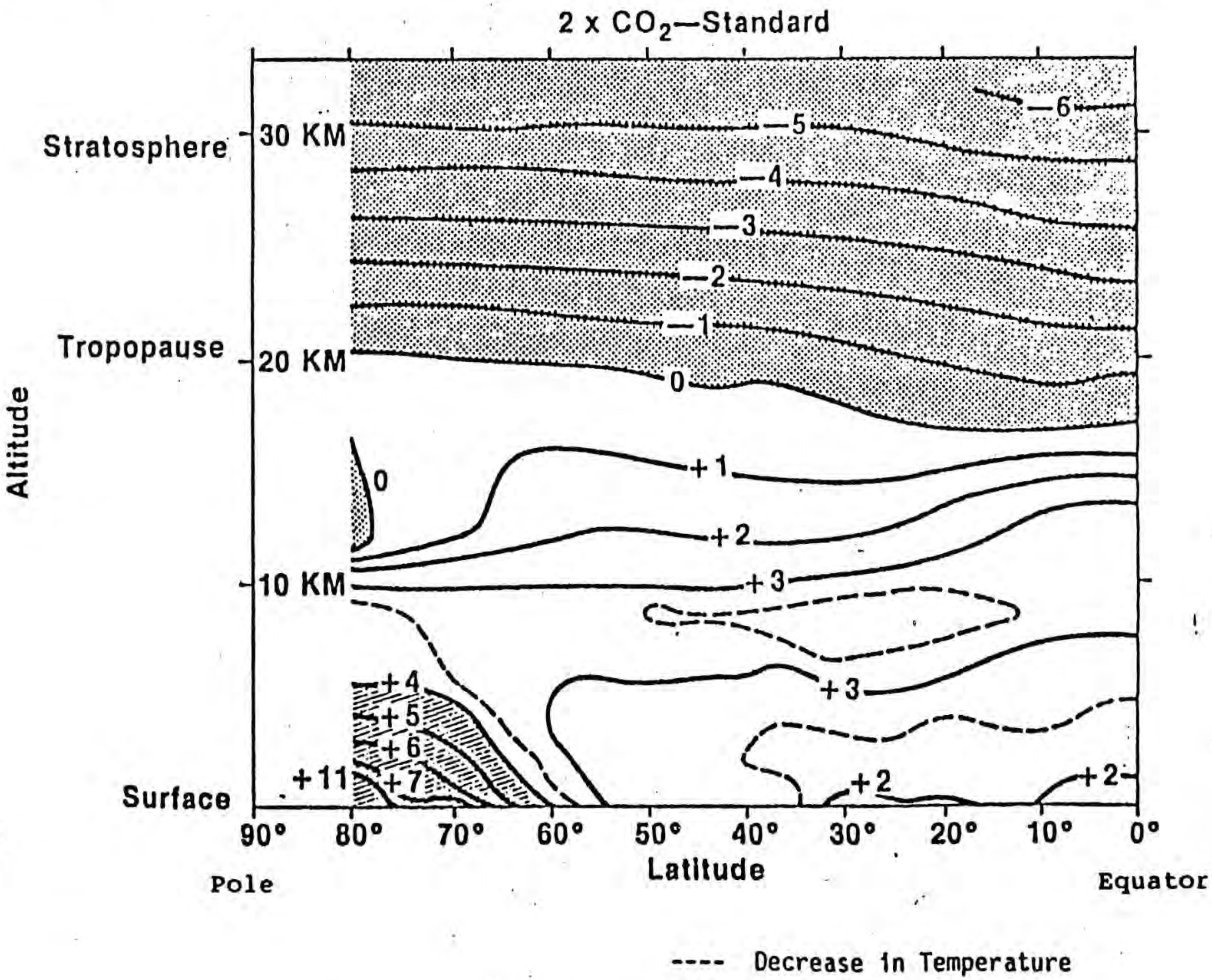
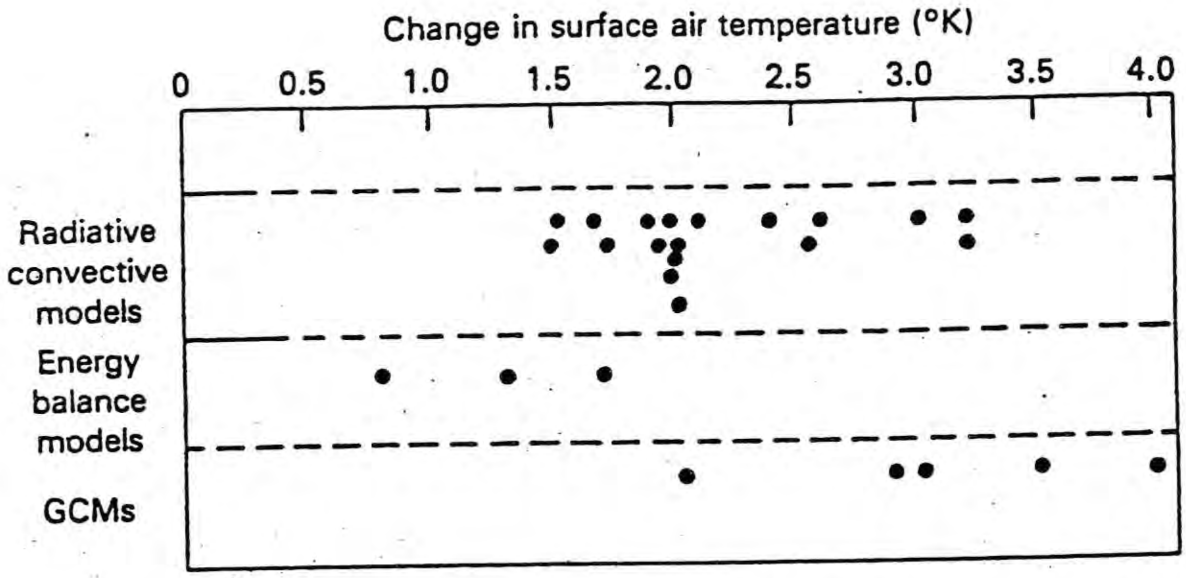


Figure 5



The change in globally averaged surface air temperature resulting from a doubling of atmospheric CO_2 as given by a variety of radiative-convective, energy balance, and global circulation (GCM) models. (From W. L. Gates, Oregon State University Technical Report no. 4.)

Figure 6

Estimates of the Change in Global Average Surface Temperature Due to Various Changes in CO_2 Concentration. Shading Shows Present Range of Natural Fluctuations.

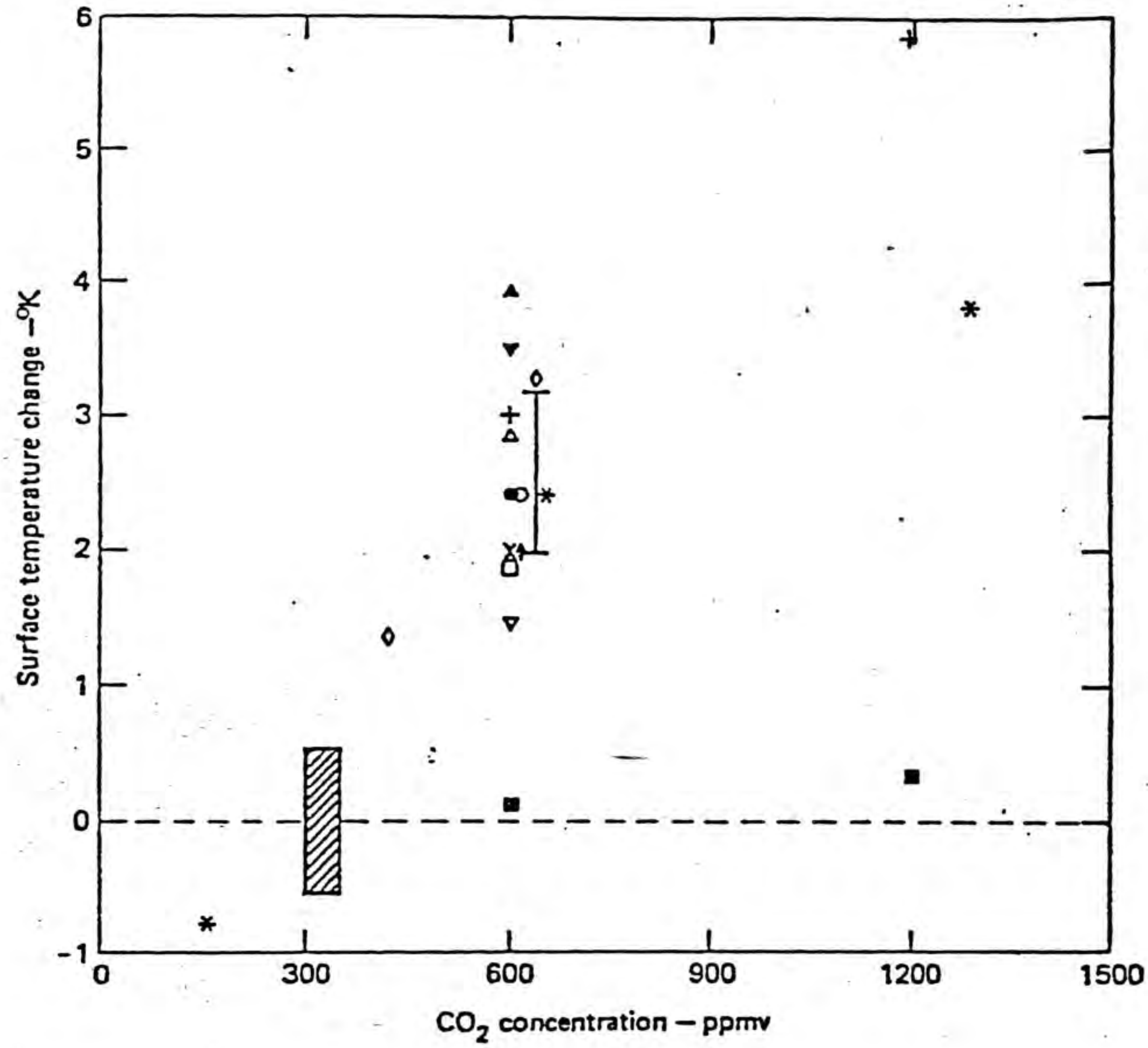
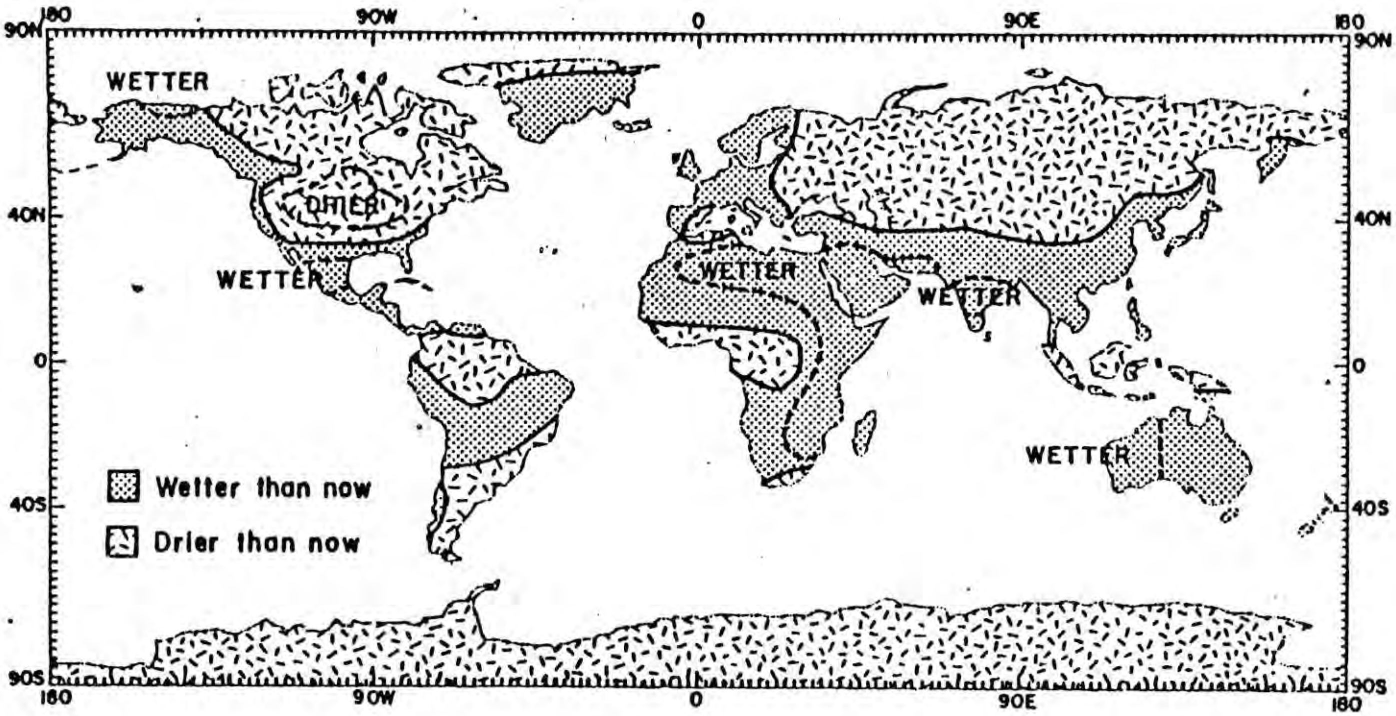


Figure 7



Example of a scenario of possible soil moisture patterns on a warmer Earth. It is based on paleoclimatic reconstructions of the Altithermal Period (4500 to 8000 years ago), comparisons of recent warm and cold years in the Northern Hemisphere, and a climate model experiment. (For a discussion of these sources of information see Appendix C.) Where two or more of these sources agree on the direction of the change we have indicated the area of agreement with a dashed line and a label.

their report titled, "Carbon Dioxide and Climate: A Scientific Assessment." This National Research Council study concluded that there are major uncertainties in these models in terms of the timing for a doubling of CO_2 and the resulting temperature increase. These uncertainties center around the thermal capacity of the oceans. The oceans have been assumed to consist of a relatively thin, well mixed surface layer averaging about 70 meters in depth in most of the general circulation models, and the transfer of heat into the deep ocean is essentially infinitely slow. The Charney panel felt, however, that the amount of heat carried by the deep ocean has been under estimated and the oceans will slow the temperature increase due to doubling of atmospheric CO_2. The Charney group estimated that the delay in heating resulting from the effect of the oceans could delay the expected temperature increase due to a doubling of CO_2 by a few decades. Accordingly, the time when the temperature increases discussed above are reached must be assumed to have occurred at an instantaneous equilibrium.

Along with a temperature increase, other climatological changes are expected to occur including an uneven global distribution of increased rainfall and increased evaporation. These disturbances in the existing global water distribution balance would have dramatic impact on soil moisture, and in turn, on agriculture. Recently, Manabe et al., using GCM's calculated that the zonal mean value of soil moisture in summer declines significantly in two separate zones of middle and high latitudes in response to an increase in the CO_2 concentration of air. This CO_2 induced summer dryness results not only from the earlier ending of the snowmelt season, but also from the earlier occurrence of the spring to summer reduction in rainfall rate. The former effect is particularly important in high latitudes, whereas the latter effect becomes important in middle latitudes. Other statistically significant changes include large increases in both soil moisture and runoff rates at high latitudes during most of the annual cycle with the exception of the summer season. The penetration of moisture rich, warm air into high latitudes is responsible for these increases.

The state-of-the-art in climate modeling allows only gross global zoning while some of the expected results from temperature increases of the magnitude indicated are quite dramatic. For example, areas that were deserts 4,000 to 8,000 years ago in the Altithermal period (when the global average temperature was some 2°C higher than present), may in due time return to deserts. Conversely, some areas which are deserts now were formerly agricultural regions. It is postulated that part of the Sahara Desert in Africa was quite wet 2,000 to 8,000 years ago. The American Midwest, on the other hand, was much drier, and it is projected that the Midwest would again become drier should there be a temperature increase of the magnitude postulated for a doubling of atmospheric CO_2 (see Figure 7).

In addition to the effects of climate on global agriculture, there are some potentially catastrophic events that must be considered. For example, if the Antarctic ice sheet which is anchored on land should melt, then this

could cause a rise in sea level on the order of 5 meters. Such a rise would cause flooding on much of the U.S. East Coast, including the State of Florida and Washington, D.C. The melting rate of polar ice is being studied by a number of glacialogists. Estimates for the melting of the West Anarctica ice sheet range from hundreds of years to a thousand years. Etkins and Epstein observed a 45 mm raise in mean sea level. They account for the rise by assuming that the top 70 m of the oceans has warmed by 0.3°C from 1890 to 1940 (as has the atmosphere) causing a 24 mm rise in sea level due to thermal expansion. They attribute the rest of the sea level rise to melting of polar ice. However, melting 51 Tt (10^{12} metric tonnes) of ice would reduce ocean temperature by 0.2°C, and explain why the global mean surface temperature has not increased as predicted by CO_2 greenhouse theories.

In an American Association for the Advancement of Science (AAAS) and Department of Energy (DOE) sponsored workshop on the environmental and societal consequences of a possible CO_2 induced climate change, other factors such as the environmental effects of CO_2 concentration on weeds and pests were considered. The general consensus was that these unmanaged species would tend to thrive with increasing average global temperature. The managed biosphere, such as agriculture, would also tend to benefit from atmospheric CO_2 growth. This is a consequence of CO_2 benefiting agriculture, provided the other key nutrients, phosphorous and nitrogen, are present in the right proportions. Agricultural water needs can be met by new irrigation techniques that require less water. In addition, with higher CO_2 and higher temperature conditions, the amount of water needed by agricultural plants may be reduced. It is expected that bioscience contributions could point the way for dealing with climatological disruptions of the magnitude indicated above. As a result of the workshop, research in 11 areas was recommended:

1. CO_2 fertilization could have broad beneficial effects on agriculture. These effects need to be studied in detail and for a variety of plant, soil and climatic conditions.

2. There is a need for a fuller understanding of the dynamics of currents and water masses in the Arctic Ocean.

3. It is necessary to determine whether there was deglaciation of the West Antarctic ice sheet about 120,000 years ago and whether this caused a rise in global sea levels at that time. If this occurred, then the information could serve as an analog of future deglaciation.

4. It is necessary to develop and use scenarios which integrate (a) information about population, resources, energy consumption and fuel mixes; (b) buildup of atmospheric CO_2; (c) response of the climate system; (d) effects on various biological systems, especially agricultural, economic and social consequences, international and interregional conflicts; and (e) possible feedback among these forces.

5. CO_2 induced warming is predicted to be much greater at the polar regions. There could also be positive feedback mechanisms as deposits of peat, containing large reservoirs of organic carbon, are exposed to oxidation. Similarly, thawing might also release large quantities of carbon currently sequestered as methane hydrates. Quantitative estimates of these possible effects are needed.

6. Although all biological systems are likely to be affected, the most severe economic effects could be on agriculture. There is a need to examine methods for alleviating environmental stress on renewable resource production — food, fiber, animal, agriculture, tree crops, etc.

7. Information exists on the relationship of cultivated and non-cultivated biomes to climatic fluctuations. Similarly, there is considerable information on the response of various nations and economic sectors to climatic variations over the past few hundred years. This information, which is currently scattered and not uniformly presented or calibrated, is thus of limited usefulness.

8. Studies of climate effects are recommended for the semi-arid tropics because of the relatively large populations in these countries and because of special sensitivity to climate.

9. There are situations (soil erosion, salinization, or the collapse of irrigation systems) which are recommended for study as indicators of how societies respond, and how they might learn to cope and adapt more effectively to a shift in global climate.

10. Research is recommended on the flow of information on risk perception and decision making to and from both laymen and experts, the physiological aspects of understanding and perception, and the factors that influence decision making.

11. There is a need to be sure that "lifetime" exposure to elevated CO_2 poses no risks to the health of humans or animals. Health effects associated with changes in the climate sensitive parameters, or stress associated with climate related famine or migration could be significant, and deserve study.

In terms of the societal and institutional responses to an increase in CO_2, the AAAS-DOE workshop participants felt that society can adapt to the increase in CO_2 and that this problem is not as significant to mankind as a nuclear holocaust or world famine. Finally, in an analysis of the issues associated with economic and geopolitical consequences, it was felt that society can adapt to a CO_2 increase within economic constraints that will be existing at the time. Some adaptive measures that were tested would not consume more than a few percent of the gross national product estimated in the middle of the next century.

Major Research Programs Underway

The Department of Energy (DOE) which is acting as a focal point for the U.S. government in this area is planning to issue two reports to the scientific community and to policy makers. The first one, summarizing five years of study is due in 1984, and the second one in 1989. The current plan is to invest approximately 10 years of research and assessment prior to recommending policy decisions in this area which impact greatly on the energy needs and scenarios for the U.S. and the world. The strategic elements of the United States national total CO_2 program are summarized in Figure 8.

Much of the government sponsored effort to date has focused on delineating the research needed to enhance our understanding of the potential problems. Accordingly, a number of workshops and symposia were held to this end. The consensus of the key research needs is summarized in Figure 8 under the heading "Research Program Results." To date, most of the research effort has been concentrated on the first two research categories. It should be noted, however, that this research started in 1979 and there are few results to report. The most ambitious project being conducted at this time is called "Transient Tracer in the Ocean (TTO)." This research, jointly funded by the DOE and the National Science Foundation (NSF), is a 4M$ project to investigate ocean mixing processes in order to enhance the understanding of how surface water CO_2 is mixed into the deep ocean. Tracers normally found in the ocean, such as ^{14}C, ^{3}H, ^{3}He, ^{85}Kr and ^{39}Ar, are monitored in the North Atlantic Ocean from oceanographic vessels.

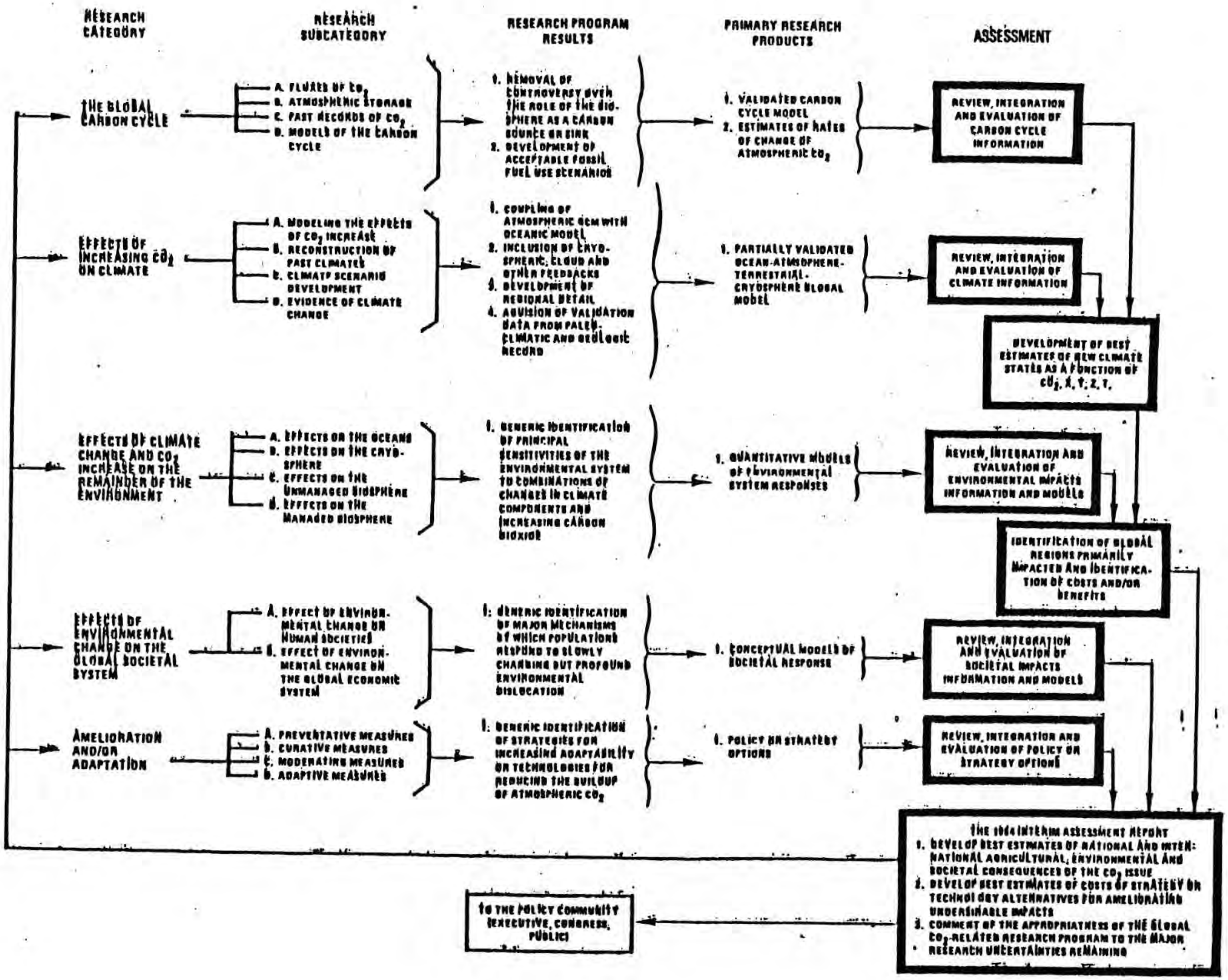
In addition to the mixing of surface waters into the bottom layers, carbon can be added to deep waters by the oxidation of organic matter and the dissolution of calcium carbonate. In order to separate these three processes and determine their relative significance, precise total carbon dioxide, alkalinity, and calcium concentration data are needed to construct and test mathematical models. Preliminary analysis of the limited data indicates that (1) lateral processes dominate the distribution of calcium and inorganic carbon in the deep oceans away from the polar regions, (2) the amount of calcium carbonate dissociated in the deep oceans is only a fraction of the previously estimated value, and (3) the excess CO_2 may have penetrated farther into the deep oceans than the currently available models predict.

Ultimately, CO_2 in the air should find its way into the deep ocean sediments. As currently understood, the deeper sediments have thus far been little affected by the fossil fuel era because of the slow mixing of the ocean. A group of scientists examined the contention that some shallow water sediments could now be dissolving and thus providing a sink for atmospheric CO_2, and concluded that the extent of dissolution is not great enough to have a large effect on the global carbon cycle.

It would be helpful if reliable estimates of the CO_2 concentration in the air could be obtained for the years prior to 1957, when the modern measurements

Figure 8

A NATIONAL PROGRAM ON CARBON DIOXIDE, ENVIRONMENT AND SOCIETY



began. Old Smithsonian Astrophysical Observatory plates of the solar spectrum taken in the early twentieth century might provide such an opportunity if they could be properly interpreted. A method for reducing the data has been developed and estimates of the CO_2 concentration should be available next year. As mentioned previously, determination of the CO_2 concentrations prior to the Industrial Revolution would help ascertain the validity of climate models, and thus the likely temperature due to a doubling of atmospheric CO_2.

Groups in Europe have used Antarctic and Greenland ice cores to independently estimate the CO_2 concentrations in the more distant past. While it is difficult to measure the CO_2 content of the dated ice cores, the results suggest that the atmospheric CO_2 concentration during the height of the last ice age (about 18,000 years ago) may have been about half its present value. This is consistent with recently published speculations derived from examination of the composition of ocean sediment cores.

There are currently approximately 40 carbon cycle and climate research projects in about 25 different institutions. Many of these projects are either supported jointly by the DOE and other agencies or exclusively by other agencies. The 1982 Federal budget request for CO_2 research was 23.9M$. The DOE, as the lead agency, would be allocated 14.0M$, NSF 6.4M$, NOAA 2.5M$, and the Department of Agriculture 1.0M$.

Future Energy Scenarios and Their Potential Impact on Atmospheric Carbon Dioxide

A number of future energy scenarios have been studied in relation to the CO_2 problem. These include such unlikely scenarios as stopping all fossil fuel combustion at the 1980 rate, looking at the delay in doubling time, and maintaining the pre-1973 fuel growth rate. Other studies have investigated the market penetration of non-fossil fuel technologies, such as nuclear, and its impact on CO_2. It should be noted, however, that fuel technology would need about 50 years to penetrate and achieve roughly half of the total market. Thus, even if solar or nuclear technologies were to be considered viable alternatives, they would not really displace fossil fuel energy for the next 40 to 50 years, and CO_2 growth would have to be estimated based on realistic market displacement of the fossil fuel technologies.

A draft report from Massachusetts Institute of Technology (MIT) and Oak Ridge (ORNL) authored by D. Rose and others considered the societal and technological inertia vis a vis decision making on the CO_2 issue. The CO_2 problem was considered as the major potential constraint on fossil fuel use. It was estimated in the study that the CO_2 problem may curtail fossil fuel use before physical depletion occurs. Considerable effort was devoted in the study to "option space," i.e., what are the potential energy alternatives, how long would it take to introduce them, and what type of material resources would be needed for effective market penetration. On reviewing the report we addressed only the technical questions relating to CO_2, and did not evaluate the plausibility of the scenarios relating to energy use in the future.

The study considered the implications of limiting atmospheric CO_2 at two different levels:

1. Rate of CO_2 addition to the atmosphere be limited to 450-500 ppm in 50 years.

2. The concentration ceiling for atmospheric CO_2 be in the range of 500-1000 ppm.

The rationale for choosing these limits is economic. If the rate of CO_2 increase is too rapid, then society may not be able to economically adapt to the resulting climate change. The second limit is based on a level where the harm due to CO_2 would greatly exceed the societal benefits that produced the CO_2. The second limit can be illustrated as an assumed threshold for inducing great irreversible harm to our planet, such as causing a large ocean level rise due to melting polar ice. In addition to improving the use of energy sources as a means of gaining time to understand the problem, it was concluded that vigorous development of non-fossil energy sources be initiated as soon as possible.

The study appears to be based on reasonable assumptions but has an inherent bias towards the accelerated development of non-fossil energy sources which, based on the present state-of-the-art, implies nuclear energy.

In his analysis, Rose introduced the concept of AIT (action initiation time), defined as the time when policies to modify or restrain fossil fuel use actually start to be effective. Based on this concept, Rose projects non-fossil growth rates of 6 to 9%/a over 40 to 50 years in order to limit atmospheric CO_2 to 500 to 700 ppm. These rates can be put in perspective by noting that such growth rates were achieved for natural gas introduction. However, nuclear or solar sources would have severe restrictions because such technologies are not as economically and politically attractive, technologically straightforward, and are encountering social and environmental opposition. In addition, Rose points out that the rate of growth of manufacturing facilities required to achieve a 6-9%/a growth rate in non-fossil fuel power generation is so large that it would be equivalent to increasing each year the U.S. power equipment manufacturing capability by an amount equivalent to the current capacity.

The study also indicated that other <u>energy-use-related</u> greenhouse gases (viz. carbon monoxide, methane, and oxides of nitrogen) may significantly contribute to a global warming. We believe the contribution of these gases to a global warming is highly speculative. Furthermore, N_2O, the only oxide of nitrogen that could contribute to a global warming is produced primarily by the microbial oxidation of ammonia from fertilizer use, and to a lesser extent from the combustion of fossil fuels. Additionally, N_2O is more reactive than CO_2 and is expected to have a relatively shorter atmospheric residence time. In

a similar vein, methane is primarily emitted to the atmosphere via the anaerobic fermentation of organic material. The contribution of anthropogenic activities (mining, industrial processes, and combustion) are 1% to 10% of the total atmospheric methane sources. The atmospheric destruction of methane is more rapid than that of CO_2, and tends to yield CO, water vapor and formaldehyde. Also, methane is believed to contribute to tropospheric ozone formation by oxidizing to CO_2. The CO in the atmosphere can be traced to anthopogenic sources (50 to 60%) and to the atmospheric oxidation of methane (30%). The major CO sink is oxidation (70 to 90%) to CO_2. One can therefore consider CO and methane as precursors to CO_2. Accordingly, CO and methane ultimately contribute to climatological effects as part of atmospheric CO_2. The N_2O, on the other hand, may not be directly related to fossil fuel combustion. One should question whether the other "greenhouse" gases should be considered part of the CO_2 problem in view of the uncertainties regarding their connection to energy use. It is not clear, at this time, whether their effect would be additive to CO_2.

Forecast Based on Fossil Fuel Projected in Exxon's Long Range Energy Outlook

As part of the Exxon 21st Century Study, the rate of fossil fuel CO_2 emissions was estimated in late 1981. Specifically, the "High Case" volumetric data provided by the Corporate Planning Department was used to estimate the potential growth of atmospheric CO_2. The volumetric data was converted to an energy basis (Quads/a = 10^{15} Btu/year) using 5.55 MBtu/B for U.S., 5.64 MBtu/B for Canada and 5.85 MBtu/B for all other countries. In addition, a shale processing loss was added using a constant rate of 27.5% of the primary energy consumption from shale. This was based on the assumption that above ground retorting of relatively high quality oil shale (>30 gallons/ton) would be recovered with a thermal efficiency of 80%, and in-situ recovery of relatively poor oil shale (>15 gallons/ton) would be accomplished with a thermal efficiency of 65%. These efficiencies were averaged over the U.S. resource base to arrive at 72.5%. Table 1 summarizes the primary energy consumption of fossil fuels.

The total carbon dioxide that can be emitted from primary fossil fuels was estimated using the following factors:

Oil = 170 lb CO_2/MBtu = 21.0 MtC*/Quad.

Gas = 115 lb CO_2/MBtu = 14.2 MtC/Quad.

Coal = 207 lb CO_2/MBtu = 25.6 MtC/Quad.

In addition, the quantity of carbon dioxide that could be emitted from the decomposition of carbonate minerals in processing U.S. oil shale was estimated by averaging this potentially large CO_2 source over the Green River formation resource base. It should be noted that poorer shale resources tend to

* MtC = million metric tons of carbon.

PRIMARY ENERGY CONSUMPTION OF FOSSIL FUELS
21st CENTURY STUDY--HIGH CASE

Quads/a

Year	1979	1990	2000	2015	2030	2050
Oil						
U.S.	37.09	33.32	32.01	35.35	36.35	36.80
Canada	4.06	4.30	4.71	5.62	6.09	5.97
Others	96.62	111.93	128.16	139.63	148.57	132.75
Total	137.77	149.55	164.88	180.60	191.01	175.52
Gas						
U.S.	20.95	17.83	17.24	15.98	16.87	17.42
Canada	1.83	2.51	2.88	3.48	4.38	4.73
Others	30.88	55.54	74.95	86.24	99.65	108.68
Total	53.66	75.88	95.07	105.70	120.90	130.83
Coal						
U.S.	14.69	20.14	28.66	37.19	43.17	55.10
Canada	0.80	1.37	1.98	2.72	3.62	5.35
Others	60.17	81.44	103.90	125.55	175.55	261.14
Total	75.66	102.95	134.54	165.41	222.54	321.59
Fossil Fuels						
World Total	267.09	328.38	394.49	451.71	534.45	627.94

Rate %/a	1979–1990	1990–2000	2000–2015	2015–2030	2030–2050
	1.90	1.85	0.91	1.13	0.81

emit much more CO_2 from carbonate minerals than the more desirable high quality resources for the same quantity of shale oil produced. It was further assumed that 65% of the carbonate minerals decompose during processing. This very conservative assumption is based on the average of 100% decomposition that may occur in "hot spots" during in-situ recovery and 30% decomposition that is generally observed in above ground retorting. Table 2 summarizes the total CO_2 produced in GtC/a. Please note that CO_2 emissions resulting from CO_2 mixed with natural gas in producing wells can be substantial, but due to the unavailability of quantitative data this factor was assumed to contribute about 5% additional CO_2 currently rising to 15% in the year 2050. This trend of CO_2 contamination of natural gas is consistent with recent Exxon experience.

The contributions of shale oil to primary fossil fuel energy and primary fossil fuel carbon are summarized in Table 3. This table shows that the fraction of shale oil CO_2 emissions to total CO_2 is greater than the corresponding contribution of shale oil energy to total energy. Table 3 also indicates the breakdown between CO_2 generated in producing and consuming shale oil, and that due to carbonate mineral decomposition.

Table 4 presents the estimated total quantities of CO_2 emitted to the environment as GtC, the growth of CO_2 in the atmosphere in ppm (v), and average global temperature increase in $^{\circ}C$ over 1979 as the base year. In order to estimate the buildup of atmospheric CO_2, it was assumed that the average atmospheric CO_2 concentration was 337 ppm in 1979. The fraction of CO_2 accumulated in the atmosphere was assumed to be 0.535 of the total fossil fuel CO_2. This number is derived from the observed historic ratio of total atmospheric CO_2 to total fossil fuel CO_2. Inherent in this number is the assumption that biomass and cement production did not contribute to atmospheric CO_2. It should be noted, however, that this method of calculation would tend to predict total anthropogenic CO_2 as long as the ratio of biomass and cement manufacture to fossil fuel consumption remains constant. The average temperature increase since 1979 was estimated, assuming that a doubling of CO_2 would cause an average global temperature increase of $3.0^{\circ} \pm 1.5^{\circ}C$. It was also assumed that fossil fuel carbon would grow at a rate of 0.8%/a between 2050 and 2080, which is a reasonable decrease from the 0.97%/a rate projected between 2030 and 2050. The following section analyzes the implications of the temperature rise due to CO_2 doubling with respect to initial detection of a greenhouse effect.

One variation of the High Case scenario was considered. It was assumed that adequate quantities of oil and gas would be discovered to exactly match those estimated to be produced from synthetic fuels in the High Case scenario, and thus balance the primary energy needs of the 21st Century Study. The net quantity of carbon that would be saved is summarized in Table 5. The implications of the synfuel losses are compared with the High Case in Figure 3. The overall impact is relatively minor.

TABLE 2

PRIMARY CARBON DIOXIDE (AS CARBON) FORMATION FROM FOSSIL FUELS 21st CENTURY STUDY--HIGH CASE

GtC/a

Year	1979	1990	2000	2015	2030	2050
Oil	2.90	3.15	3.47	3.79	4.01	3.69
Inorganic Carbon	-	0.01	0.05	0.19	0.27	0.40
Total Oil	2.90	3.16	3.52	3.98	4.28	4.09
Gas	0.76	1.08	1.35	1.50	1.72	1.86
CO_2 in Gas	0.04	0.11	0.15	0.18	0.22	0.28
Total Gas	0.80	1.19	1.50	1.68	1.94	2.14
Total Coal	1.93	2.64	3.45	4.24	5.70	8.24
World Total	5.63	7.00	8.47	9.90	11.92	14.47
Rate %/a	2.00	1.92	1.05	1.25	0.97	0.80

TABLE 3

OIL SHALE LIQUID FUELS
PRIMARY ENERGY CONSUMPTION AND
CARBON DIOXIDE (AS CARBON) PRODUCTION
21st CENTURY STUDY--HIGH CASE

Year	1979	1990	2000	2015	2030	2050
U.S. Shale, Quads/a	--	1.01	3.65	14.38	20.66	30.79
Other Shale	--	0.21	1.49	2.56	5.55	11.10
Total	--	1.21	5.14	16.94	26.21	41.89
% Primary Shale Energy/Primary Fossil Fuels Energy	--	0.35	1.30	3.75	4.90	6.67
Shale Carbon, GtC/A	--	0.03	0.11	0.36	0.55	0.88
Carbonate Carbon	--	0.01	0.05	0.19	0.27	0.40
Total	--	0.04	0.16	0.55	0.82	1.28
% Primary Shale Carbon/Primary Fossil Fuel Carbon	--	0.55	1.89	5.55	6.87	8.85

TABLE 4

ESTIMATED ATMOSPHERIC CO_2 CONCENTRATION AND AVERAGE TEMPERATURE INCREASE
21st CENTURY STUDY--HIGH CASE

Year	Emitted, GtC		Stored in Atmosphere, GtC		Atmospheric Concentration, ppm		Average Temperature Increase, °C
	Incremental	Cummulative	Incremental	Cummulative	Incremental	Cummulative	
1979	--	--	--	715	--	337	0
1990	69.3	69.3	37.1	752	17.5	355	0.22
2000	77.2	146.5	41.3	793	19.5	374	0.45
2015	137.5	284.0	73.6	867	34.7	409	0.84
2030	163.3	447.3	87.4	954	41.2	450	1.25
2050	263.5	710.8	141.0	1095	66.5	516	1.84
2080	490.6	1201.4	262.5	1358	123.7	640	2.78
2090	191.3	1392.7	102.3	1160	48.2	688	3.09

TABLE 5

ESTIMATED INCREMENTAL CO_2 CONTRIBUTION FROM SYNTHETIC FUELS TO ATMOSPHERIC CO_2 CONCENTRATION AND AVERAGE GLOBAL TEMPERATURE INCREASE

GtC/a

Year	1990	2000	2015	2030	2050	2080
Shale Loss	0.004	0.025	0.069	0.114	0.181	
Carbonate Decomposition	0.013	0.047	0.186	0.267	0.398	
Total Shale	0.017	0.072	0.255	0.381	0.579	
Coal Loss	0.018	0.067	0.136	0.276	0.535	
Total Synfuels Loss	0.035	0.139	0.391	0.657	1.114	
Rate %/a		14.8	7.1	3.5	2.7	2.0
Incremental CO_2, GtC	-	0.80	3.73	7.73	17.38	45.79
Cummulative CO_2, GtC	-	0.80	4.53	12.26	29.64	75.43
Incremental Atmospheric CO_2, ppm	-	0.2	0.9	1.9	4.4	11.5
Cummulative Atmospheric CO_2, ppm	-	0.2	1.1	3.1	7.5	19
Net Atmospheric CO_2, ppm	355	374	407	446	506	616
Average Temperature Increase, °C	0.22	0.45	0.82	1.21	1.76	2.61

Detection of a CO_2 Greenhouse Effect

It is anticipated by most scientists that a general consensus regarding the likelihood and implications of a CO_2 induced greenhouse effect will not be reached until such time as a significant temperature increase can be detected above the natural random temperature fluctuations in average global climate. These fluctuations are assumed to be $\pm0.5^\circ C$. The earliest that such discreet signals will be able to be measured is one of the major uncertainties of the CO_2 issue.

A number of climatologists claim that they are currently measuring a temperature signal (above climate noise) due to a CO_2 induced greenhouse effect, while the majority do not expect such a signal to be detectable before the year 2000. In order to quantify the implications of detecting a greenhouse effect now, as opposed to the year 2000, estimates were made on temperature projections as a function of the CO_2 concentration that existed prior to the Industrial Revolution. Available data on CO_2 concentration prior to the Industrial Revolution tend to fall into two groups: 260 to 270 ppm or 290 to 300 ppm. In Table 6, possible temperature increases were estimated as a function of initial CO_2 concentrations of 265 and 295 ppm. Temperatures were projected for three cases, viz., (1) a temperature increase of $3^\circ C$ occurs if current CO_2 concentration doubles, (2) the greenhouse effect is detectable now (1979), and (3) the greenhouse affect is detected in the year 2000.

One can see in Table 6 that if a doubling of atmospheric CO_2 will cause a $3^\circ C$ rise in temperature, then we should have seen a temperature increase above climate noise if initial CO_2 concentration was 265 ppm, or be on the threshold of detecting such an effect now, if the initial concentration was 295 ppm. If we assume that we are on the threshold of detecting a greenhouse effect, then the average temperature due to a doubling of CO_2 will be $1.9^\circ C$ for an initial CO_2 concentration of 265, or $3.1^\circ C$ for an initial concentration of 295 ppm. Finally, if the greenhouse effect is detected in the year 2000, then the doubling temperature for initial CO_2 concentrations of 265 and 295 ppm will be 1.3° and $1.7^\circ C$, respectively. Based on these estimates, one concludes that a doubling of current concentrations of CO_2 will probably not cause an average global temperature rise much in excess of $3^\circ C$, or the effect should be detectable at the present time. Alternatively, if the greenhouse effect is not detected until 2000, then the temperature due to a CO_2 doubling will probably be under $2^\circ C$. Using the Exxon 21st Century Study as a basis for fossil fuel growth patterns, the average global temperature increases due to CO_2 would range between 0.8 and $1.6^\circ C$ by 2030. A doubling of atmospheric CO_2 would be extropolated from the fossil fuel consumption rates of the 21st Century Study to occur at about the year 2090 with the temperature increase ranging between 1.3° and $3.1^\circ C$. The projected range presented above is considerably lower than the generally accepted range of 1.5° to $4.5^\circ C$. Figure 9 illustrates

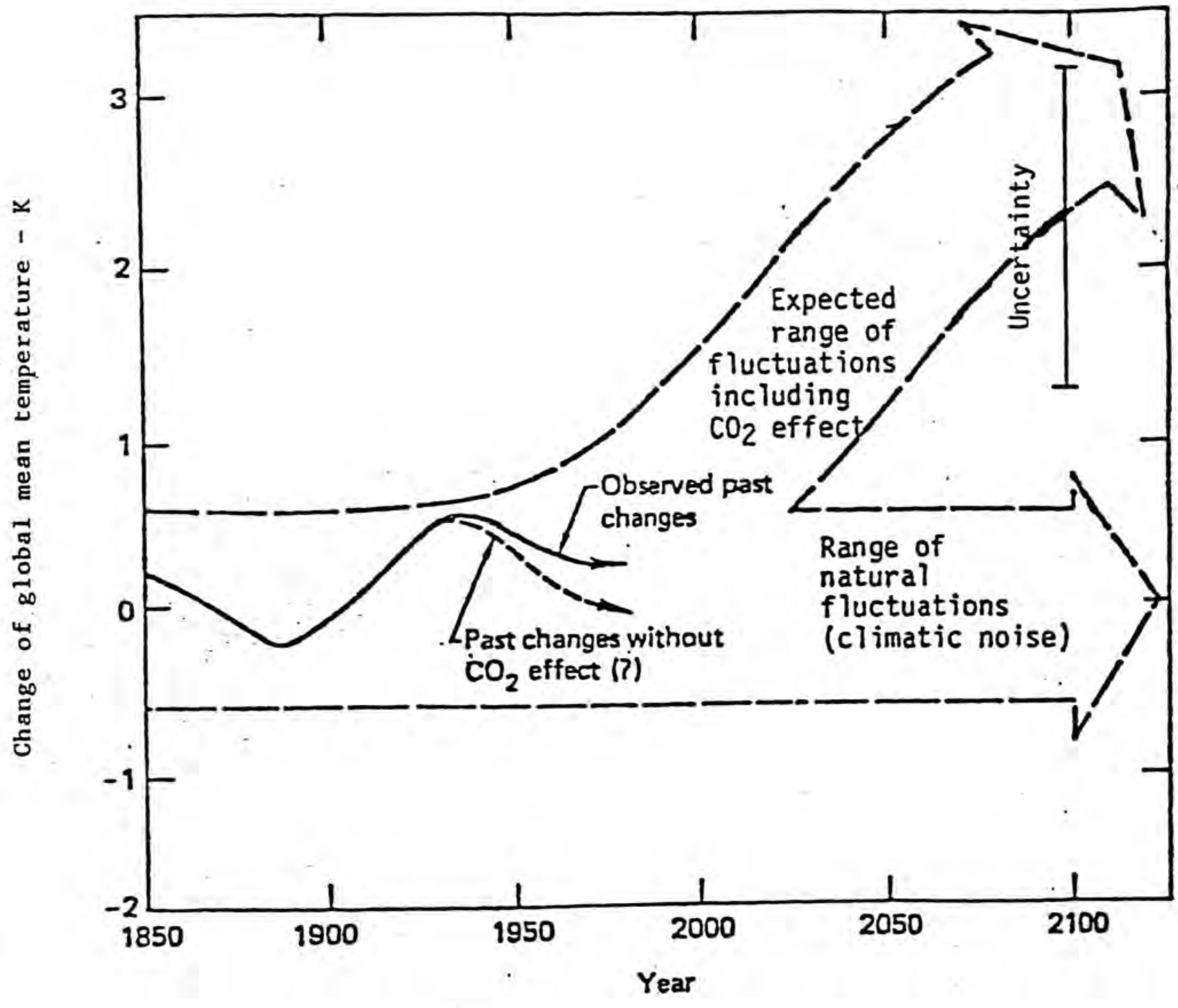
TABLE 6

EFFECT OF PRE-INDUSTRIAL ATMOSPHERIC CO_2 CONCENTRATION ON GLOBAL AVERAGE TEMPERATURE INCREASE

Atmospheric CO_2 Concentration, ppm	Time (Instantaneous Equilibrium)	Temperature, °C: Doubling ~2090		Detected 1979		Detected 2000	
		265	295	265	295	265	295
1,000	~2140	4.3	4.4	2.8	4.6	1.9	2.5
800	~2110	3.6	3.6	2.3	3.7	1.4	2.1
674 (Doubling)	~2090	3.0	3.0	1.9	3.1	1.3	1.7
451	2030	1.7	1.5	1.1	1.6	0.8	0.9
375	2000	1.1	0.9	0.7	0.9	0.5	0.5
337 (Current)	1979	0.8	0.5	0.5	0.5	0.3	0.3
295	~1850	0.3	0	0.2	0	0.2	0
265	~1850	0	-	0	-	0	-

Figure 9

Range of Global Mean Temperature From 1850 to the Present with the Projected Instantaneous Climatic Response to Increasing CO_2 Concentrations.



the behavior of the mean global temperature from 1850 to the present, contained within an envelop scaled to include the random temperature fluctuations, and projected into the future to include the 1.3° to 3.1°C range of uncertainty noted above for the CO_2 effect.

Depending on the actual global energy demand and supply, it is possible that some of the concerns about CO_2 growth due to fossil fuel combustion may be reduced if fossil fuel use is decreased due to high price, scarcity, and unavailability.

The above discussion assumes that an instantaneous climatic response results from an increase in atmospheric CO_2 concentration. In actuality, the temperature effect would likely lag the CO_2 change by about 20 years because the oceans would tend to damp out temperature changes.

Given the long term nature of the potential problem and the uncertainties involved, it would appear that there is time for further study and monitoring before specific actions need be taken. At the present time, that action would likely be curtailment of fossil fuel consumption which would undoubtedly seriously impact the world's economies and societies. Key points needing better definition include the impact of fossil fuel combusion and the role of the oceans in the carbon cycle and the interactive effect of carbon dioxide and other trace atmospheric gases on climate.

BIBLIOGRAPHY

Ad Hoc Study Group on Carbon Dioxide and Climate. 1979. Carbon Dioxide and Climate: A Scientific Assessment. Wash. DC: Nat. Acad. Sci. 25 pp.

Adams, J. A. S., Mantovani, M. S. M., Lundell, L. L. 1977. Wood versus fossil fuel as a source of excess carbon dioxide in the atmosphere: A preliminary report. Science 196:54-56.

American Friends Service Committee (AFSC) 1972. The Agnes Diaster and the Federal Response. Philadelphia, Pa.: AFSC.

Andrews, J. T., Mears, A., Miller, G. H., Pheasant, D. R. 1972. Holocene late glacial maximum and marine transgression in the Eastern Canadian Arctic. Nature Phys. Sci. 239:147-49.

Arrhenius, S. 1896. On the fluence of carbonic acid in the air upon the temperature of the ground. Philos. Mag. 41:237-76.

Augustsson, T., Ramanathan, V. 1977. A radiative-convective model study of the CO_2 climate problem. J. Atmos. Sci. 34:448-51.

Bacastow, R. 1979. Dip in the atmospheric CO_2 level during the mid 1960s. J. Geophys. Res. 84:3108-14.

Bacastow, R. 1976. Modulation of atmospheric carbon dioxide by the Southern Oscillation. Nature 261:116-18.

Bacastow, R. B., Keeling, C. D. 1973. Atmospheric carbon dioxide and radio carbon in the natural carbon cycle: Changes from A.D. 1700 to 2070 as deduced from a geochemical model. In Carbon and the Biosphere. CONF 720510, ed. G. M. Woodwell, E. V. Pecan, pp. 86-135. Springfield, Va.: NTIS.

Bach, W. 1976. Global Air Pollution and Climate Change. Rev. Geophys. Space Phys. 14:429-74.

Bach, W., Pankrath, J., Williams, J. 1980. Interactions of Energy and Climate. D. Reidel, Dordrecht, Holland.

Baes, C. F. Jr., Goeller, H. E., Olsen, J. S., Rotty, R. M. 1977. Carbon Dioxide and Climate: The Uncontrolled Experiment. Am. Sci. 65:310-20.

Baker, E. J., McPhee, J. G. 1975. Land Use Management and Regulation in Hazardous Areas: A Research Assessment, Boulder, Co: Inst. Behav. Sci. 124 pp.

Barney, G. O. 1980. The global 2000 report to the President. A report prepared by the Council on Environmental Quality and the Department of State. NTIS.

Berger, R., and Libby, W. F. 1960. Equilibration of Atmospheric Carbon Dioxide with Sea Water: Possible Enzymatic Control of the Rate. Science. 1395-6.

Boisvert, R. N. 1975. Impact of Floods and Flood Management Policy on Area Economic Development and Recovery. Dept. Agric. Econ., Cornell Univ., Ithaca, NY. 71 pp.

Bolin, B., Degeus, E. T., Kempe, S., Ketner, P., eds. 1979. The Global Carbon Cycle, SCOPE 13. New York: Wiley. 491 pp.

Bolin, B. 1977. Changes of land biota and their importance for the carbon cycle. Science. 196:613-15.

Bolin, B., Bischof, W. 1970. Variations of the carbon dioxide content of the atmosphere in the northern hemisphere. Tellus 29:171-80.

Broeker, W. S. 1975. Climatic Change: Are We on the Brink of a Pronounced Global Warming? Science. 189:460-3.

Broecker, W. S., Takahashi, T., Simpson, H. J., Peng, T. -H. 1979. Fate of fossil fuel carbon dioxide and the global carbon budget. Science. 206:409-18.

Broecker, W. S., Thurber, D. L., Goodard, J., Ku, T. -L., Matthews, R. K., Mesolella, K. J. 1968. Milankovitch hypothesis supported by precise dating of coral reefs and deep-sea sediments. Science. 159:298-300.

Bryan, K., Komro, F. G., Manabe, S., Spelman, M. J. 1982. Transient climate response to increasing atmospheric carbon dioxide. Science. 215:56-8.

Bryson, R. A., Wendland, W. M., Ives, J. E., Andrews, J. T. 1969. Radiocarbon isochrones on the disintegration of the Laurentide ice sheet. Arctic Alpine Res. 1:1-14.

Budd, W., McInnes, B. 1978. Modeling surging glaciers and periodic surging of the Antarctic ice sheet. In Climatic Change and Variability: A Southern Perspective. ed. A. B. Pittock, L. A. Frakes, D. Jenssen, J. A. Peterson, J. W. Zillman, pp. 228-34. New York: Cambridge Univ. Press. 455 pp.

Budd, W. F., Jenssen, D., Radok, U. 1971. Derived Physical Characteristics of the Antarctic Ice Sheet, Mark 1. Univ. Melbourne Meteor. Dept. Publ. No. 18, Melbourne, Australia. 178 pp.

Callendar, G. S. 1938. The artificial production of carbon dioxide and its influence on temperature. Q. J. Roy. Meteor. Soc. 64:223-27.

Carbon Dioxide and Climate Research Program. 1979. Summary of the Carbon Dioxide Effects Research and Assessment Program. U. S. Dept. of Energy. Wash. D.C. 37 pp.

Cess, R. D., Hameed, S., Hogan, J. S. 1980. Response of the global climate to changes in atmospheric chemical composition due to fossil fuel burning. ASME Paper 80-WA/HT-3.

Chen, K., Winter, R. C., Bergman, J. K. 1980. Carbon Dioxide from Fossil Fuels-Adapting to Uncertainty. Energy Policy, 8:318-330.

Choudhury, B., Kukla, G. 1979. Impact of CO_2 on cooling of snow and water surfaces. Nature. 280:668-71.

Clark, J. A., Lingle, C. S. 1977. Future sea-level changes due to West Antarctic ice sheet fluctuations. Nature. 269:206-9.

Climate Research Board. 1979. Toward a U.S. Climate Program Plan. Wash. D.C.: Nat. Acad. Sci. 91 pp.

Cochrane, H. C., Haas, J. E., Bowden, M. J., Kates, R. W. 1974. Social Science Perspectives on the Coming San Francisco Earthquake: Economic Impact, Prediction and Reconstruction. Natural Hazard Res. Working Pap. No. 25, Inst. Behav. Sci., Univ. Colo., Boulder, Co. 82 pp.

Colvill, A. J. 1977. Movement of Antarctic ice fronts measured from satellite imagery. Polar Record. 18:390-94.

Committee on Climate and Weather Fluctuations and Agricultural Production. 1979. Climate and Food. Wash. D.C.: Nat. Acad. Sci. 212 pp.

Council on Environmental Quality. 1981. Global energy futures and the carbon dioxide problem.

Dacy, D. D., Kunreuther, H. 1969. The Economics of Natural Disasters. New York: The Free Press.

Delmas, R. J., Ascencio, J. M., Legrand, M. 1980. Polar ice evidence that atmospheric CO_2 20,000 yr BP was 50% of present. Nature. 284:155-7.

Denton, G. H., Armstrong, R. L., Stuiver, M. 1971. The late Cenozoic glacial history of Antarctica. In The Late Cenozoic Glacial Ages, ed. K. Turekian, pp. 267-306. New Haven: Yale Univ. Press.

Economic Development Council of Northeastern Pennsylvania. 1972. Economic Impact of Tropical Storm Agnes on Luzerne County. Flood Recovery Task Force, Inc. Philadelphia, Pa.

Enrlich, P. R., Ehrlich, A. H., Holdren, J. P. 1977. Ecoscience. San Francisco: Freeman. 1051 pp.

Etkins, R., Epstein, E. S. 1982. The rise of global mean sea level as an indication of climate change. Science. 215:287-9.

Elliott, W. P., Machta, L., eds. 1979. Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels. CONF-770385, Springfield, Va: NTIS. 122 pp.

Flohn, H. 1974. Background of a geophysical model of the initiation of the next glaciation. Quat. Res. 4:385-404.

Flohn, H. 1978. Abrupt events in climatic history. Climatic change and variability: A southern perspective, Ed. A. B. Pittock, et al., New York: Cambridge Univ. Press. pp 124-34.

Flohn, H. 1980. Possible climatic consequences of a man-made global warming. IIASA Report RR-80-30. 92 pp.

Garvey, E. A., Prahl, R., Nazimek, K., Shaw, H. 1982. Exxon global CO_2 measurement system. IEEE Trans. on Instr. and Measur. IM-31:32-36.

Geophysics Study Committee. 1977. Climate, Climatic Change and Water Supply. Wash. D. C. Nat. Acad. Sci. 132 pp.

Gilmour, A. E. 1979. Ross ice shelf sea temperature. Science. 203:438-39.

Ginsburg, N. 1972. The lure of tidewater: The problem of the interface between land and sea. In Pacem in Maribus, ed. E. M. Borgese, pp. 32-41. New York: Dodd Mead. 382 pp.

Giovinetto, M. B. 1970. The Antarctic ice sheet and its bimodel response to climate. In Int. Symp. Antarctic Glaciol. Explor. Int. Assoc. Sci. Hydrology (IASH) Commission on Snow and Ice. Publ. No. 86, pp. 347-58. Wash. D.C.: IASH (c/o Am. Geophys. Union).

Glantz, M. 1979. A political view of CO_2. Nature. 280:189-90.

Gornitz, V., Lebedeff, S., and Hansen, J. 1982. Global sea level trend in the past century. Science. 215:1611-4.

Hameed, S., Cess, R. D. 1980. Impact of a global warming on biospheric sources of methane and its climatic consequences. ASME Paper 80-WA/HT-2.

Hameed, S., Cess, R. D., Hogan, J. S. 1980. Response of the global climate to changes in atmospheric chemical composition due to fossil fuel burning. J. Geophys. Res. 85:7537-45.

Hansen, J., et. al., 1981. Climate impact of increasing atmospheric carbon dioxide. Science. 213:957-66.

Hirschler, M. M. 1981. Man's emission of carbon dioxide into the atmosphere. Atmos. Environ. 15:719-27.

Hoffert, M. I. 1974. Global distributions of atmospheric carbon dioxide in the fossil-fuel era: A projection. Atmos. Envir. 8:1225-49.

Hollin, J. T. 1965. Wilson's theory of ice ages. Nature. 208:12-16.

Hollin, J. T. 1969. Ice sheet surges and the geological record. Can. J. Earth Sci. 6:903-10.

Hollin, J. T. 1972. Interglacial climates and Antarctic ice surges. Quat. Res. 2:401-8.

Hoyt, D. V. 1979. An emperical determination of the heating of the earth by the carbon dioxide greenhouse effect. Nature. 282:388-90.

Hughes, T. 1973. Is the West Antarctic ice sheet disintegrating? J. Geophys. Res. 78:7844-7910.

Hughes, T. 1977. West Antarctic ice streams. Rev. Geophys. Space Phys. 15:1-46.

Hughes, T. 1975. The West Antarctic ice sheet: Instability, disintegration and initiation of ice ages. Rev. Geophys. Space Phys. 13:502-26.

Hughes, T. 1980. Climatic warming and collapse of the West Antarctic Ice Sheet. In Workshop on Environmental and Societal Consequences of a Potential CO_2 Induced Climate Warming. Wash. D.C.: USDOE. In press.

Idso, S. B. 1980. The climatological significance of a doubling of earth's atmospheric carbon dioxide concentration. Science 207:1462-3.

Ives, J. D., Andrews, J. T., Barry, R. G. 1975. Growth and decay of the Laurentide ice sheet and comparisons with Fenno-Scandinavia. Naturwissenschaften 62:118-25.

Jacobs, S. S., Gordon, A. L., Ardai, J. L. Jr., 1979. Circulation and melting beneath the Ross ice shelf. Science 203: 439-43.

Jason. 1979. The Long Term Impact of Atmospheric Carbon Dioxide on Climate. Tech. Rep. JSR-78-07. SRI Int., Arlington, Va. 184 pp.

Jason. 1980. The Carbon Dioxide Problem: DOE Program and General Assessment. Tech. Rep. JSR-80-06. SRI Int., Arlington, VA. 37 pp.

Kahn, H., Brown, W., Martel, L. 1976. The Next 200 Years: A Scenario for America and the World. New York: Morrow. 241 pp.

Keeling, C. D., Bacastow, R. B. 1977. Impact of industrial gases on climate. In Energy and Climate, ed. Geophys. Res. Board, pp 72-95. Wash. D.C.: Nat. Acad. Sci. 158 pp.

Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdahl, C. A., Jr., Guenther, P. R., Waterman, L. S., Chin, J. F. S. 1976. Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. Tellus 28:538-51.

Keeling, C. D., Adams, J. A. Jr., Ekdahl, Jr., C. A., Guenther, P. R. 1976. Atmospheric carbon dioxide variations at the South Pole. Tellus. 28:552-64.

Kellogg, W. W., Schneider, S. H. 1978. Global air pollution and climate change. IEEE Trans. Geosci. Electron. GE16:44-50.

Kellogg, W. W., 1977. Effects of human activities on global climate. WMO Tech. Note No. 156. WMO No. 486, World Meteor. Org., Geneva Switz. 47 pp.

Kellogg, W. W., Mead, M., eds. 1977. The atmospheric resources: Will mankind behave rationally? In The Atmosphere: Endangered and Endangering. Fogarty Intl. Cent. Proc. No. 39, Publ. No. NIH 77-1065. Wash. D.C.: Nat. Inst. Health, pp. 75-92.

Kellogg, W. S., Schwave, R. 1981. Climate Change and Society. Westview Press, Colorado.

Kneese, A. V. 1977. Economics and the Environment. New York: Penguin.

Kopec, R. J. 1971. Global climate change and the impact of a maximum sea level on coastal development. J. Geog. 70:541-50.

Kukla, G., and Gavin, J. 1981. Recent Changes in The Snow and Ice Marginal Belt. Science. 214:497-503.

Laurmann, J. A. 1979. Market penetration characteristics for energy production and atmospheric carbon dioxide growth. Science 205:896-98.

Lave, L. B., Seskin, E. P. 1977. Air Pollution and Human Health. Baltimore: John Hopkins Univ. 368 pp.

MacDonald, G. J. F. 1978. An overview of the impact of carbon dioxide on climate. Mitre Corporation Report M78-79.

Machta, L., Telegades, K. 1974. In Weather and Climate Modification, ed. W. N. Hess, pp. 697-725. New York: Wiley.

Machta, L. 1972. Mauna Loa and global trends in air quality. Bull. Am. Meteor, Soc. 53-402:20.

Madden, R. A., Ramanathan, V. 1980. Detecting climate change due to increasing carbon dioxide. Science. 209:763-8.

Manabe, S., Wetherald, R. T. 1975. The effects of doubling the CO_2 concentration on the climate of a general circulation model. J. Atmos. Sci. 32:3-15.

Manabe, S., Wetherald, R. T. 1980. On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere. J. Atmos. Sci. 37:99-118.

Manabe, S., Wetherald, R. T., Stouffer, R. T. 1981. Summer Dryness Due to an Increase of Atmospheric CO_2 Concentration. Climate Change. 3:347-86.

Marchetti, C. 1975. Chem. Econ. Eng. Rev. 7:9-15.

Marchetti, C. 1977. On geoengineering and the CO_2 problem. Climatic Change. 1:59-68.

Marland, G., Rotty, R. M. 1979. Carbon dioxide and climate. Rev. Geophys. Space Phys. 17:1813-24.

McRae, J. E., Graedel, T. E. 1979. Carbon dioxide in the urban atmosphere: Dependencies and trends. J. Geophys. Res. 84:5011-17.

Meadows, D. H., Meadows, D. L., Randers, J., Behrens, W. W. III. 1972. The Limits to Growth. New York: Universe Books, 241 pp.

Mercer, J. H. 1978. West Antarctic ice sheet and CO_2 greenhouse effect: A threat of disaster. Nature 277:321-25.

Mercer, J. 1968. Antarctic ice and Sangamon sea level. In Int. Assoc. Sci. Hydrol. Commission of Snow and Ice, General Assembly of Bern, Publ. No. 79, pp. 217-25.

Meyer-Abich, K. 1980. Socioeconomic impacts of climate changes and the comparative changes of alternative political responses — prevention, compensation and adaptation. Climatic Change 3 (No. 3) In Press.

Michel, R. L., Linick, R. W., Williams, P. M. 1979. Tritium and Carbon-14 distributions in seawater from under the Ross ice shelf project ice hole. Science 203:445-46.

Mileti, D. S. 1975. Natural Hazard Warning Systems in the United States: A Research Assessment. Inst. Behav. Sci., Univ. Colo., Boulder, Colo. 97 pp.

National Climate Program Office. 1979. National Climate Program Preliminary 5-year Plan. NOAA. Wash. D.C. 150 pp.

National Defense University. 1978. Climate Change to the Year 2000. Wash. D.C.: Nat. Defense Univ. 109 pp.

Neumann, A. D., Moore, W. S. 1975. Sea level events and Pleistocene coral ages in the northern Bahamas. Quat. Res. 5:215-24.

Newell, R. E., Dopplick, T. G. 1979. Questions concerning the possible influence of anthropogenic CO_2 on atmospheric temperature. J. Appl. Meteor. 18:822-5.

Niethaus, F. 1976. A non-linear eight level tandem model to calculate the future CO_2 and C-14 burden to the atmosphere. IIASA Rep. RM-76-35, Int. Inst. Appl. Syst. Anal., Laxenburg, Austria.

Nordhaus, W. D. 1977. Economic growth and climate: The carbon dioxide problem. AM. Econ. Rev. 67:341-46.

Panel on the Public Policy Implications of Earthquake Prediction. 1975. Earthquake Prediction and Public Policy. Wash. D.C.: Nat. Acad. Sci. 142 pp.

Pearman, G. I. 1977. Further studies of the comparability of baseline atmospheric carbon dioxide measurements. Tellus 29: 171-80.

Pearson, C., Pryor, A. 1977. Environment: North and South — An Economic Interpretation. New York: Wiley 355 pp.

Perry, A. M. Fulkerson, W. 1982. Energy supply and demand implications of CO_2. Presented at the AAAS Meeting, Washington D.C.

Ramanathan, V., Lian, M. S., Cess, R. D. 1979. Increased atmospheric CO_2: Zonal and seasonal estimates of the effect on the radiation energy balance and surface temperature. J. Geophys. Res. 84:4949-58.

Rasmussen, R. A., Khalil, M. A. K. 1981. Increase in the concentration of atmospheric methane. Atmos. Environ. 15:883-6.

Risk/Impact Panel. 1980. Report of the Risk/Impact Panel of the U.S. NRC Comm. on Nuclear and Alternative Energy Systems. Risks and Impacts of Alternative Energy Systems. Wash. D.C.: Nat. Acad. Sci. In Press.

Robin, G. de Q. 1975. Ice shelves and ice flow. Nature 253:168-72.

Rust, B. W., Rotty, R. M., Marland, G. 1979. Inferences drawn from atmospheric CO_2 data. J. Geophys. Res. 84:3115-22.

Schneider, S. H. 1975. On the carbon dioxide-climate confusion. J. Atmos. Sci. 32-2060-66.

Schneider, S. H., Temkin, R. L. 1977. In Climatic Change, ed. J. Gribbin, pp. 228-46. Oxford: Cambridge Univ. Press.

Schneider, S. H., Washington, W. M., Chervin, R. M. 1978. Cloudiness as a climatic feedback mechanism: Effects on cloud amounts of prescribed global and regional surface temperature changes in the NCAR GCM. J. Atmos Sci. 35:2207-21.

Schneider, S. H., Thompson, S. L. 1979. Carbon dioxide and climate change: Importance of the transient response. J. Geophys. Res. Submitted for publication.

Schneider, S. H., with L. E. Mesirow, 1976. The Genesis Strategy: Climate and Global Survival. New York: Plenum. 419 pp.

Schneider, S. H. 1979. Comparative Risk Assessment of Energy Systems. Energy — the International Journal 4:919-31.

Schneider, S. H. Chen, R. S. 1980. Carbon dioxide warming and coastline flooding: Physical factors and climate impact. Ann. Rev. Energy. 5:107-40.

Schneider, S. H., Morton, L. 1981. The Primordial Bond: Exploring Connections Between Man and Nature Through the Humanities and the Sciences. New York: Lleunum. In Press.

Seiler, W., Crutzen, P. J. 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Climatic Change. 2:207-47.

Siegenthaler, U., Oeschger, H. 1978. Predicting future atmospheric carbon dioxide levels. Science. 199:388-95.

Smil, V., Miltin, D. 1974. Carbon dioxide — alternative futures. Atmos. Envir. 8:1213-23.

Stuiver, M. 1978. Atmospheric carbon dioxide and carbon reservoir changes. Science 199:253-58.

Study of Man's Impact on Climate (SMIC). 1971. Inadvertent Climate Modification: Report of the Study of Man's Impact on Climate. Cambridge, Mass.: MIT Press 308 pp.

Sugden, D. E., Clapperton, C. M. 1980. West Antarctic ice sheet fluctuations in the Antarctic peninsula area. Nature. 286-378-81.

Sunquist, E. T., Miller, G. A. 1980. Oil shales and carbon dioxide. Science. 208:740-1.

Suomi, V. E., Chairman Climate Research Board, NRC. 1980. A strategy for the National Climate Program. National Academy of Sciences.

Takahashi, I., Yoshino, M. M. 1978. Climate Change and Food Production. Tokyo: Univ. Tokyo Press. 433 pp.

Thomas, R. H., Sanderson, T. J. O., Rose, R. E. 1979. Effect of climatic warming on the West Antarctic ice sheet. Nature 277:355-58.

Thomas, R. 1979. Ice sheets and ice shelves. Rev. Geophys. Space Phys. 17:1257-58, 1273-76.

Thomas, R. H. 1979. West Antarctic ice sheet: Present day thinning and holocene retreat of the margins. Science. 205:1257-58.

Thomas R. H. 1976. Thickening of the Ross Ice Shelf and equilibrium state of the West Antarctic ice sheet. Nature 259-180-83.

Thompson, S. L., Schneider, S. H. 1979. A seasonal zonal energy balance climate model with an interactive lower layer. J. Geophys. Res. 84:24-01-14.

U. S. Comm. for Global Atmos. Res. Program. 1975. Understanding Climatic Change: A Program for Action. Wash. D.C.: Nat. Acad. Sci. 239 pp.

Weertman, J. 1976. Glaciology's grand unsolved problem. Nature 260:284-86.

Weertman, J. 1974. Stability of the junction of an ice sheet and an ice shelf. J. Glaciol 13:3-11.

Williams, J. ed. 1978. Carbon Dioxide, Climate and Society. New York: Pergamon. 332 pp.

Wilson, A. T. 1969. The climatic effects of large-scale surges of ice sheets. Can J. Earth Sci. 6:911-18.

Wang, W. C., Yung, Y. L., Lacis, A. A., Mo, T., Hansen, J. E. 1976. Greenhouse effects due to man-made perturbations of trace gases. Science. 194:685-90.

Wittwer, S. H. 1980. Carbon dioxide and climate change: an agricultural perspective. J. Soil and Water Conserv. 35:116-120.

Wong, C. S. 1978. Carbon dioxide — A global environmental problem in the future. Marine Pollution Bulletin. 9:257-64.

Woodwell, G. M., Whittaker, R. H., Reiners, W. A., Likens, G. E., Delwiche, C. C., Botkin, D. B. 1978. The biota and the world carbon budget. Science 199:141-46.

Woodwell, G. M. 1978. The carbon dioxide question. Scientific American. 238:34-43.

EXHIBIT 22

RECEIVED
NOV 1982

AS GIVEN

DR. E. E. DAVID, JR.
PRESIDENT, EXXON RESEARCH AND ENGINEERING COMPANY

REMARKS AT THE FOURTH ANNUAL EWING SYMPOSIUM
TENAFLY, NEW JERSEY
OCTOBER 26, 1982

INVENTING THE FUTURE: ENERGY AND THE CO_2 "GREENHOUSE" EFFECT

DENNIS GABOR, A WINNER OF THE NOBEL PRIZE FOR PHYSICS, ONCE REMARKED THAT MAN CANNOT PREDICT THE FUTURE, BUT HE CAN INVENT IT. THE POINT IS THAT WHILE WE DO NOT KNOW WITH CERTAINTY HOW THINGS WILL TURN OUT, OUR OWN ACTIONS CAN PLAY A POWERFUL ROLE IN SHAPING THE FUTURE. NATURALLY, GABOR HAD IN MIND THE POWER OF SCIENCE AND TECHNOLOGY, AND THE MODEL INCLUDES THAT OF CORRECTION OR FEEDBACK.

IT IS AN IMPORTANT THOUGHT: MAN DOES NOT HAVE THE GIFT OF PROPHECY. ANY MANAGER OR GOVERNMENT PLANNER WOULD ERR SERIOUSLY BY MASTERMINDING A PLAN BASED UNALTERABLY ON SOME VISION OF THE FUTURE, WITHOUT PROVISION FOR MID-COURSE CORRECTION. IT IS ALSO A COMFORTING THOUGHT. WITH MAN'S NOTORIOUS INABILITY TO CREATE RELIABLE PREDICTIONS ABOUT SUCH MATTERS AS ELECTIONS, STOCK MARKETS, ENERGY SUPPLY AND DEMAND, AND, OF COURSE, THE WEATHER, IT IS A GREAT CONSOLATION TO FEEL THAT WE CAN STILL RETAIN SOME CONTROL OF THE FUTURE.

AS YOU MAY KNOW, EXXON IS A HUNDRED YEARS OLD THIS YEAR; WE HAVE A LONG CORPORATE MEMORY OF THE VERY PROFOUND SOCIAL AND ECONOMIC TRANSFORMATIONS THAT OUR BUSINESS ACTIVITIES HAVE HELPED BRING ABOUT, AND OF HOW WE AND SOCIETY HAVE HAD TO ADAPT FURTHER IN RESPONSE. THAT INCLUDES THE AT LEAST TEMPORARY RESPITE GIVEN TO THE WHALES THROUGH SUBSTITUTING KEROSENE LIGHTING FUEL FOR THEIR RENDERED BLUBBER; AS WELL AS THE REVOLUTIONARY CHANGES WROUGHT BY THE AUTOMOBILE AND OTHER MACHINERY POWERED BY LIQUID HYDROCARBON FUELS. THE PRIMARY FACTORS GUIDING SUCH DEVELOPMENTS WERE TECHNOLOGY AND ECONOMIC MARKETS, THOUGH POLITICAL SYSTEMS ALSO PLAYED THEIR ROLE.

BUT FAITH IN TECHNOLOGIES, MARKETS, AND CORRECTING FEEDBACK MECHANISMS IS LESS THAN SATISFYING FOR A SITUATION SUCH AS THE ONE YOU ARE STUDYING AT THIS YEAR'S EWING SYMPOSIUM. THE CRITICAL PROBLEM IS THAT THE ENVIRONMENTAL IMPACTS OF THE CO_2 BUILDUP MAY BE SO LONG DELAYED. A LOOK AT THE THEORY OF FEEDBACK SYSTEMS SHOWS THAT WHERE THERE IS SUCH A LONG DELAY THE SYSTEM BREAKS DOWN UNLESS THERE IS ANTICIPATION BUILT INTO THE LOOP. THE QUESTION THEN BECOMES HOW TO ANTICIPATE THE FUTURE SUFFICIENTLY FAR IN ADVANCE TO PREPARE FOR IT.

ONE ANSWER IS TO INVENT THE FUTURE IN ANOTHER WAY--THROUGH A SYSTEM OF CONTINGENCY PLANNING BASED ON AN ASSESSMENT OF A NUMBER OF FUTURES. AS HARVEY BROOKS HAS NOTED, SCENARIOS HAVE LIMITED USE IF THEY ARE MERELY "SURPRISE FREE" PROJECTIONS OF CURRENT TRENDS; INSTEAD, THEY MUST SOMEHOW TAKE INTO ACCOUNT THOSE CLOUDS ON THE HORIZON NO BIGGER THAN A MAN'S HAND THAT CAN TURN OUT TO BE DOMINANT INFLUENCES IN TWENTY YEARS. INADEQUATE SCENARIO-MAKING EXPLAINS THE POOR PERFORMANCE OF MOST SOCIAL RESEARCH TO DATE--WHICH SO OFTEN GIVES THE SENSE OF TOO LITTLE TOO LATE, WHETHER THE TOPIC IS TOXIC WASTE, FROST BELT AND SUN BELT, OR THE SHIFT FROM MANUFACTURING TO INFORMATION SOCIETY. THE KEY IS TO UNDERTAKE RESEARCH THAT WILL TEND TO BE INDEPENDENT OF FUTURE EVENTS, OR, RATHER, <u>RELEVANT</u> ACROSS A BROAD SPECTRUM OF SCENARIOS.

THIS IS NOT EASY TO DO, BUT SOME OF EXXON'S OWN RESEARCH AND DEVELOPMENT STRATEGY IS AIMED IN THAT DIRECTION. AND EXXON IS NOT THE ONLY COMPANY WITH THIS ATTITUDE. THAT IS

WHY WE AND OTHERS IN THE PETROLEUM INDUSTRY HAVE TAKEN A STRONG INTEREST IN THE ISSUE OF THE GREENHOUSE EFFECT AND YOUR WORK. IT IS WHY WE HAVE PARTICIPATED IN SEVERAL INITIATIVES TO PROMOTE YOUR RESEARCH; IT IS WHY WE ARE PLEASED TO CONTRIBUTE TO THE HOLDING OF THIS SYMPOSIUM AND TO PARTICIPATE IN IT. AND IT IS WHY WE HAVE BEGUN OUR OWN MODEST RESEARCH EFFORT IN THE FIELD, MOTIVATED ALSO BY THE BELIEF THAT PERHAPS THE ONLY WAY TO UNDERSTAND A FIELD IS TO DO RESEARCH IN IT. YOU HAVE SEEN SOME OF THE RESULTS IN A PAPER DELIVERED YESTERDAY AFTERNOON. WE ARE ALSO IN THE PROCESS OF EVALUATING THE DATA ON CO_2 CONCENTRATIONS COLLECTED OVER TWO YEARS BY AN EXXON TANKER PLYING BETWEEN THE GULF OF MEXICO AND THE GULF OF ARABIA.

ORGANIZATION

FEW PEOPLE DOUBT THAT THE WORLD HAS ENTERED AN ENERGY TRANSITION AWAY FROM DEPENDENCE UPON FOSSIL FUELS AND TOWARD SOME MIX OF RENEWABLE RESOURCES THAT WILL NOT POSE PROBLEMS OF CO_2 ACCUMULATION. THE QUESTION IS HOW DO WE GET FROM HERE TO THERE WHILE PRESERVING THE HEALTH OF OUR POLITICAL, ECONOMIC, AND ENVIRONMENTAL SUPPORT SYSTEMS. WHAT I WILL DO IN THE REMAINDER OF THIS TALK IS INDICATE HOW THE WORLD MAY INVENT A SUCCESSFUL ENERGY FUTURE, USING THE SORT OF CORRECTIVE FEEDBACK SYSTEM I HAVE DESCRIBED. MY PERSPECTIVE IS OF COURSE AN EXXON PERSPECTIVE, REFLECTING OUR OWN ASSUMPTIONS ABOUT THE ECONOMIC AND SOCIAL PATHS SOCIETIES WILL PREFER. AND SINCE FOSSIL FUELS, AND LIQUID CHEMICAL FUELS, ARE REALLY THE HEART OF THE ENERGY AND THE CO_2 PROBLEM, I WILL FOCUS ON THOSE.

My plan of attack is, first, to consider the implications of recent energy developments. Then I will describe some of the key assumptions that are guiding Exxon's own R&D planning and which, I think, we have in common with many other actors on the scene. Finally, I will go on to mention some of the technical possibilities that may present themselves well beyond our usual twenty-year outlook period, that is, fifty years or more into the future.

While I am far from certain about the details, I think you'll find that I'm generally upbeat about the chances of coming through this most adventurous of all human experiments with the ecosystem.

Recent Energy History

It is ironic that the biggest uncertainties about the CO_2 buildup are not in predicting what the climate will do, but in predicting what people will do. The scientific community is apparently reaching some consensus about the general mechanisms of the greenhouse effect. It is considerably less agreed on how much fossil fuels mankind will burn; how fast economies will grow; what energy technologies societies will foster and when; and so how fast the buildup will occur.

But we do know about the recent past and the present. In the aftermath of the energy price increases of the past decade, consumers have reacted to the price feedback mechanism very much as classic economic theory would predict. They have

SHARPLY REDUCED THEIR ENERGY CONSUMPTION AND, IN PARTICULAR, THEIR CONSUMPTION OF OIL. THEY HAVE SUBSTITUTED OTHER FUELS LIKE COAL AND NUCLEAR FOR PETROLEUM, ALTHOUGH MORE COAL USE DOES INCREASE CO_2 EMISSIONS. CONSUMERS HAVE ALSO CONSERVED BY TURNING TO MORE ENERGY EFFICIENT TECHNOLOGIES, INCLUDING SMALLER CARS IN THE U.S. AND THEY HAVE DONE WITHOUT.

IT IS DIFFICULT TO DISENTANGLE THE EFFECTS OF CONSERVATION FROM THE EFFECTS OF RECESSION. ACCORDING TO A RECENT REPORT FROM THE INTERNATIONAL ENERGY AGENCY, THEY ARE ABOUT EQUAL. WE THINK CONSERVATION EFFECTS ARE LARGER, BUT REGARDLESS, ENERGY CONSUMERS HAVE CERTAINLY BROKEN THE LOCK-STEP RELATIONSHIP BETWEEN ECONOMIC ACTIVITY AND ENERGY CONSUMPTION THAT SEEMED TO PREVAIL FOR A QUARTER CENTURY FOLLOWING WORLD WAR II. FOR EXAMPLE, ACCORDING TO THE INTERNATIONAL ENERGY AGENCY, IT NOW TAKES 16 PERCENT LESS ENERGY AND 26 PERCENT LESS OIL TO PRODUCE 1 PERCENT MORE OF OUTPUT IN THE NON-COMMUNIST INDUSTRIALIZED COUNTRIES THAN IN 1973.

THIS DEVELOPMENT CARRIES GREAT SIGNIFICANCE FOR THE CO_2 BUILDUP. CONSUMERS AND TECHNOLOGISTS HAVE BEEN INVENTING AND APPLYING A WEALTH OF METHODS TO EXTRACT MORE WORK FROM LESS ENERGY. FOR EXAMPLE, AS ONE OF OUR OWN BIGGEST ENERGY CUSTOMERS, WE AT EXXON HAVE STEPPED UP THE EFFICIENCY OF OUR REFINERIES BY TWENTY PERCENT SINCE 1973. BECAUSE REFINING IS SO ENERGY-INTENSIVE, THE ENERGY SAVINGS, AND THE CORRESPONDING REDUCTIONS OF CO_2 EMISSIONS, HAVE BEEN VERY LARGE INDEED. LAST YEAR THE SAVINGS AMOUNTED TO THE EQUIVALENT OF SOME 28 MILLION BARRELS OF

OIL--EQUAL TO THE PRODUCTION FROM A WORLD-SCALE, 50,000-BARREL-PER-DAY SYNTHETIC FUELS PLANT. ON TOP OF THAT, WE HAVE SET THE GOAL OF DOUBLING OUR REFINING EFFICIENCY BY THE YEAR 2000, AND WE THINK THE GOAL IS REALISTIC.

HOW FAR WILL THE CONSERVATION TREND GO? IT IS TOO EARLY TO SAY FOR SURE, BUT WE THINK THE IMPLICATIONS APPLY VERY FAR INTO THE FUTURE. AND HOW FAR WILL THE ENERGY MIX TEND TO FAVOR FUELS, SUCH AS COAL, THAT PRODUCE LARGE AMOUNTS OF CO_2, RATHER THAN FUELS WITH HIGH RATIOS OF HYDROGEN TO CARBON, SUCH AS GASOLINE AND METHANE? TO SOME EXTENT THE ANSWER TO THAT QUESTION DEPENDS UPON OUR ABILITY TO COME UP WITH A SOURCE OF LOW COST HYDROGEN BASED ON NON-FOSSIL ENERGY--A POINT I'LL RETURN TO LATER.

FOSSIL FUEL OUTLOOK: KEY ASSUMPTIONS

IN ASSESSING ALTERNATIVE FUTURES, I WOULD OFFER THREE ASSUMPTIONS IN THE FORM OF PREDICTIONS ABOUT THE USE OF ENERGY AND FOSSIL FUELS.

FIRST, NEARLY ALL SOCIETIES WILL CONTINUE TO GIVE PRIMACY TO ECONOMIC GROWTH. THE HUMAN DESIRE TO IMPROVE MATERIAL CONDITIONS BURNS AS BRIGHT AS EVER, IF NOT BRIGHTER. AS WE HAVE SEEN MOST RECENTLY IN POLAND, GOVERNMENTS THAT FAIL TO DELIVER AT LEAST A CONVINCING PROMISE OF GROWTH SUFFER DIRE CONSEQUENCES AS A RULE. WITH THE OVERALL WORLD POPULATION EXPECTED TO DOUBLE OVER THE NEXT 50 YEARS, ECONOMIES AND ENERGY USE WILL HAVE TO GROW AT A GOOD CLIP JUST TO HOLD PER CAPITA INCOMES EVEN.

NATURALLY, THE PRESSURES FOR GROWTH WILL BE GREATEST IN THE DEVELOPING WORLD, WHERE POPULATIONS ARE GROWING FASTEST.

A SECOND ASSUMPTION, ONE THAT FOLLOWS FROM THE FIRST, IS THAT IN PURSUIT OF GROWTH MOST SOCIETIES WILL PREFER LEAST-COST ENERGY ALTERNATIVES. I SAY THIS WITH THE RECOGNITION THAT AT LEAST A FEW DEVELOPING COUNTRIES WILL PREFER OPTIONS THAT UTILIZE LOCAL RESOURCES IN ORDER TO CONSERVE FOREIGN EXCHANGE OR USE LOCAL LABOR, NO MATTER WHAT THE COST. AN EXAMPLE IS BRAZIL'S RESORT TO ALCOHOL FUELS EXTRACTED FROM ITS SUGAR CANE. HOWEVER, SUCH EXCEPTIONS WILL NOT MATERIALLY ALTER THE WORLD FUTURE.

THE THIRD ASSUMPTION IS THAT SOCIETIES WILL CONTINUE TO PREFER THE EFFICIENCIES OF FOSSIL-BASED LIQUID FUELS IN TRANSPORTATION USES. BECAUSE CONVENTIONAL PETROLEUM RESOURCES WILL NOT SUFFICE TO MEET THE DEMAND, A MAJOR INDUSTRY WILL BEGIN TO GROW AROUND THE TURN OF THE CENTURY TO PRODUCE SYNTHETIC FUELS FROM OIL SANDS, OIL SHALE, AND COAL.

DESPITE THE TREND TOWARD ELECTRICITY, THE ELECTRIC VEHICLE WILL HAVE TROUBLE MAKING SIGNIFICANT INROADS IN TRANSPORTATION MARKETS OVER THE NEXT TWENTY YEARS. ONE PROBLEM IS STORAGE, WHICH IS PARTLY A PROBLEM OF ENERGY DENSITY. TODAY'S LEAD-ACID BATTERIES STORE ABOUT 1/300TH THE ENERGY OF A LIKE WEIGHT OF GASOLINE. WE CAN IMPROVE ON THAT; IN FACT, EXXON IS IN THE MIDDLE OF DEVELOPING A ZINC-BROMINE BATTERY WITH TWO TO THREE TIMES THE CAPACITY OF CONVENTIONAL LEAD-ACID BATTERIES. ANOTHER PROBLEM IS THE COST OF BATTERIES. THEY ARE EXPENSIVE, MAINLY BECAUSE OF THE COST OF RAW MATERIALS AND TYPICALLY SHORT LIFE

CYCLES. INCIDENTALLY, WE EXPECT THAT LOAD LEVELING, RATHER THAN THE ELECTRIC CAR, WILL BE ONE OF THE EARLIEST APPLICATIONS OF OUR NEW BATTERY. HOWEVER, WE WOULD CERTAINLY NOT RULE OUT THE ELECTRIC CAR ONE DAY--PERHAPS INITIALLY IN THE FORM OF HYBRID VEHICLES POWERED BY BATTERIES IN TANDEM WITH SMALL GASOLINE OR DIESEL ENGINES.

ANOTHER ALTERNATIVE FEATURES ELECTRIC GUIDEWAY SYSTEMS IN WHICH VEHICLES USE BATTERIES ON THE FEEDER ROADS AND ELECTRICALLY INDUCED POWER ALONG THE MAIN ARTERIES. BUT THE CAPITAL COSTS OF SUCH A SYSTEM WOULD BE IMMENSE--MAKING IT A VIABLE OPTION ONLY FOR MUCH RICHER SOCIETIES THAN WE CAN FORESEE.

GRANTED, LIQUID FUELS--LIKE ALL CHEMICAL FUELS--HAVE THEIR SHARE OF PROBLEMS. IN BURNING THEY MAY SYNTHESIZE SOME UNFRIENDLY SUBSTANCES-- SUCH AS PNA'S, NO_x, SO_x AND CO_2. STILL, THERE ARE ALSO WELL-KNOWN PROBLEMS WITH PRODUCING ELECTRICITY THROUGH NON-CHEMICAL MEANS, SUCH AS NUCLEAR POWER. SOLAR VOLTAICS OVERCOME MANY OF THESE DRAWBACKS, BUT THE INHERENT PROBLEMS OF THE DUTY CYCLE AND STORAGE MAKE ME SKEPTICAL THAT SOLAR VOLTAICS WILL PENETRATE A LARGE FRACTION OF THE ELECTRICITY MARKET IN THE NEAR FUTURE, EXCEPT IN REMOTE APPLICATIONS.

BUT TO REITERATE MY MAIN THEME, SUCH ASSUMPTIONS ONLY ACT AS A GUIDE IN DETERMINING WHERE R&D MANAGERS CAN MOST USEFULLY CONCENTRATE RESOURCES FOR INVENTING THE FUTURE, SUBJECT TO CORRECTION AND FURTHER FEEDBACK. IN ANY CASE WE ARE NOT UP AGAINST FATAL, MALTHUSIAN LIMITS TO GROWTH. ON THE DISTANT HORIZON, WE MAY DISCERN A PEAKING OF PETROLEUM PRODUCTION;

BECAUSE FOR MORE THAN A DECADE THE WORLD HAS BEEN CONSUMING PETROLEUM FASTER THAN THE INDUSTRY HAS BEEN REPLACING IT. BUT REMAINING NON-PETROLEUM FOSSIL FUEL RESOURCES ARE IMMENSE. AS AN EXAMPLE, IN 1980 OIL AND GAS PRODUCTION ACCOUNTED FOR NEARLY 70 PERCENT OF THE WORLD'S PRODUCTION OF FOSSIL ENERGY. BUT OIL AND GAS RESERVES ACCOUNT FOR ONLY A LITTLE OVER 11 PERCENT OF THE WORLD'S ESTIMATED TOTAL RECOVERABLE FOSSIL ENERGY RESOURCES.

AS A PRACTICAL MATTER, YOU WOULD SURELY AGREE THAT THE WORLD ECONOMY IS COMMITTED TO USING FOSSIL RESOURCES FOR SOME TIME TO COME. THE MASSIVENESS OF THE ENERGY SYSTEM IN PLACE SIMPLY FORBIDS IMMEDIATE DISPLACEMENT OF ONE FUEL OR ENERGY SOURCE BY ANOTHER. HISTORICAL MARKET STUDIES GOING BACK TO WOOD AND COAL CONFIRM THIS IDEA, SUGGESTING THAT A NEW ENERGY SOURCE REQUIRES ABOUT <u>50 YEARS</u> TO ACHIEVE JUST HALF THE TOTAL ENERGY MARKET.

WHAT ARE EXXON'S PROJECTIONS FOR FOSSIL FUEL USE? OVER THE TWENTY YEARS ENCOMPASSED BY OUR NORMAL OUTLOOK WE ESTIMATE THAT FOSSIL FUEL USE WILL GROW AT THE EQUIVALENT OF ABOUT TWO PERCENT PER YEAR. MUCH OF THIS GROWTH WILL OCCUR IN THE DEVELOPING COUNTRIES, AS THEY MODERNIZE THEIR ECONOMIES.

BEYOND OUR NORMAL TWENTY-YEAR OUTLOOK PERIOD, WE RECENTLY ATTEMPTED A FORECAST OF THE CO_2 BUILDUP. WE ASSUMED DIFFERENT GROWTH RATES AT DIFFERENT TIMES, BUT WITH AN AVERAGE GROWTH RATE IN FOSSIL FUEL USE OF ABOUT ONE PERCENT A YEAR STARTING TODAY, OUR ESTIMATE IS THAT THE DOUBLING OF ATMOSPHERIC CO_2 LEVELS MIGHT OCCUR SOMETIME LATE IN THE 21ST CENTURY. THAT

INCLUDES THE IMPACTS OF A SYNFUELS INDUSTRY. ASSUMING THE GREENHOUSE EFFECT OCCURS, RISING CO_2 CONCENTRATIONS MIGHT BEGIN TO INDUCE CLIMATIC CHANGES AROUND THE MIDDLE OF THE 21ST CENTURY.

MANUFACTURING SYNTHETIC FUELS WILL PRODUCE MORE CO_2 THAN CONVENTIONAL PETROLEUM FUELS, BUT THE IMPACT OF SUBSTITUTING SYNTHETICS FOR DEPLETING PETROLEUM SUPPLIES WILL BE RELATIVELY SMALL. IF, IN OUR ESTIMATE, WE BACK OUT SYNFUELS, AND REPLACE THEM WITH CONVENTIONAL PETROLEUM FUELS, THE DIFFERENCE IN CO_2 EMISSIONS WOULD ONLY ADD ABOUT FIVE YEARS TO THE DOUBLING TIME. THIS IS A HIGHLY CONSERVATIVE ESTIMATE, BECAUSE IT ASSUMES THAT INDUSTRY IN THE 21ST CENTURY WILL CONTINUE USING TODAY'S "DINOSAUR" TECHNOLOGIES FOR MANUFACTURING SYNFUELS, WITH NO INCREASE IN THE EFFICIENCY OF THESE HIGHLY ENERGY-INTENSIVE PROCESSES. AND IT TAKES NO NOTICE OF THE TRENDS WE ARE ALREADY SEEING TODAY IN THIS BUDDING INFORMATION AGE. AS JOHN PIERCE, THE INVENTOR OF SATELLITE COMMUNICATIONS, LIKES TO SAY, SOON WE MAY BE TRAVELING FOR PLEASURE BUT COMMUNICATING TO WORK. SUCH DEVELOPMENTS COULD EVENTUALLY GO VERY FAR IN REDUCING THE ENERGY INTENSITY AND CO_2 EMISSIONS OF ADVANCED ECONOMIES.

EXXON'S RESPONSE IN SCIENCE AND TECHNOLOGY

THE REAL POINT OF THESE EXTRAPOLATIONS IS TO GET AN UNDERSTANDING OF HOW SOON THE PROBLEM MAY BECOME SERIOUS ENOUGH TO REQUIRE ACTION. AND THE LESSON IS THAT, WHILE THE ISSUE IS CLEARLY IMPORTANT, WE CAN STILL AFFORD FURTHER RESEARCH ON THE PROBLEM. AND THE WORLD WILL HAVE TIME TO ACCUMULATE THE MATERIAL

AND SCIENTIFIC RESOURCES REQUIRED TO CONTEND WITH THE PROBLEM.

THE SAME POINT IS EMPHASIZED IN THE ENERGY STUDY PUBLISHED LAST YEAR BY THE INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, OR IIASA. THE STUDY INVOLVED SOME 150 TOP SCIENTISTS AT ONE TIME OR ANOTHER AND REPRESENTS ONE OF THE MOST COMPREHENSIVE ASSESSMENTS OF THE OUTLOOK FOR THE NEXT 50 CRITICAL YEARS OF WHAT MAY WELL BE IN ABSOLUTE TERMS THE WORLD'S PERIOD OF GREATEST POPULATION GROWTH.

THE IIASA STUDY CONCLUDES THAT TO MAKE A SUCCESSFUL TRANSITION FROM FOSSIL FUELS TO AN ENERGY SYSTEM BASED ON RENEWABLE RESOURCES, THE WORLD ECONOMY MUST EXPAND ITS PRODUCTIVE POWERS. IT MUST EXPAND IN ALL DIMENSIONS, BUT, MOST IMPORTANTLY, IN THE NEW KNOWLEDGE AND HUMAN SKILL THAT ENLARGE THE TECHNOLOGICAL BASE. FOR SUCH KNOWLEDGE AND SKILL, MORE THAN BRUTE CAPITAL, IS WHAT ENABLES SOCIETIES IN THIS AGE TO USE THE SAME OR EVEN FEWER RESOURCES TO PRODUCE MORE.

THE IIASA STRATEGY FOR INVENTING THAT FUTURE RESEMBLES THE ONE I HAVE SUGGESTED: A STRATEGY FIRST, OF GRADUAL TRANSITION FROM CLEAN, HIGH QUALITY RESOURCES--NATURAL GAS AND OIL--TO DIRTIER UNCONVENTIONAL FOSSIL RESOURCES. THE STUDY ALSO TAKES NOTE OF THE CO_2 ISSUE, RECOMMENDING THAT SOCIETY INCORPORATE SUFFICIENT NON-FOSSIL OPTIONS IN THE ENERGY SUPPLY SYSTEM SO AS TO ALLOW EXPANSION OF THAT BASE, IF NECESSARY, AS THE EFFECTS OF CARBON DIOXIDE BECOME BETTER QUANTIFIABLE THROUGH FURTHER RESEARCH.

THAT MEANS PURSUING RESEARCH LEADS IN TECHNOLOGIES THAT MAY NOT SEEM ATTRACTIVE BY THE FASHIONABLE STANDARDS OF FINANCIAL ANALYSIS. IN A RECENT LANDMARK ARTICLE, PROFESSORS HAYES AND ABERNATHY OF THE HARVARD BUSINESS SCHOOL WARN STRONGLY AGAINST SUCH FINANCIALLY BIASED PRACTICES IN AMERICAN INDUSTRY; TRYING TO OUTGUESS THE ECONOMICS OF UNTRIED AND UNTESTED TECHNOLOGICAL APPROACHES CAN BE THE DEATH OF AN INDUSTRY, AND I MIGHT ADD, OF A SOCIETY, TOO. SOME OF THE TOOLS OF THIS TRADE--FOR EXAMPLE, DISCOUNTED CASH FLOW ANALYSIS--ARE COMPLETELY UNREALISTIC. SOMETIMES THEY ARE CALLED THE ASTROPHYSICS OF A NON-EXISTENT UNIVERSE.

AS I HAVE ALREADY SUGGESTED, EXXON'S OWN R&D PHILOSOPHY DICTATES SEARCHING FOR A DIVERSIFIED MIX OF SHORT- AND LONG-RANGE TECHNOLOGICAL OPTIONS. I HAVE ALREADY ALLUDED TO OUR EFFORTS TO BOOST THE ENERGY EFFICIENCY OF OUR REFINERIES--A HIGHLY IMMEDIATE AND APPARENT NEED TO MANAGEMENT. THIS NEED IS APPARENT EVEN THOUGH OUR R&D IN SOME AREAS MAY NOT PAY OUT FOR YEARS--FOR EXAMPLE, IN ADVANCED SEPARATION SYSTEMS THAT DO NOT EMPLOY NORMAL HEAT DISTILLATION TECHNIQUES. ANOTHER OF OUR MAJOR THRUSTS IS IN DEVELOPING MORE VERSATILE TECHNOLOGIES FOR CONVERTING CRUDE RESIDUUMS TO LIGHT TRANSPORTATION FUELS. THE NEED STEMS FROM AN EVIDENT SHIFT OF DEMAND IN THAT DIRECTION AND FROM THE REDUCED QUALITY OF THE AVERAGE CRUDE OIL TODAY. EXXON HAS BEGUN DEPLOYMENT OF AN INNOVATION IN THIS AREA CALLED FLEXICOKING, A PROCESSING "GARBAGE CAN" THAT CAN CONVERT VIRTUALLY ANY HEAVY CRUDE OR RESIDUUM INTO TRANSPORTATION FUELS AND FUEL GAS.

AS INDUSTRY MOVES DOWN TO LOWER QUALITY RESOURCES, THERE IS SYNERGISM BETWEEN SUCH "RESID" CONVERSION TECHNOLOGIES AND OUR EFFORTS TO DEVELOP IMPROVED SYNTHETICS TECHNOLOGIES. WITH THE EXCEPTION OF ESTABLISHED SYNTHETICS OPERATIONS IN SOUTH AFRICA AND CANADA, FALLING CRUDE PRICES AND ESCALATING PROJECT COSTS HAVE NIPPED THE SYNTHETIC FUELS INDUSTRY IN THE BUD. MANY SYNTHETICS TECHNOLOGIES HAVE TURNED OUT TO BE FAR MORE EXPENSIVE THAN ANYONE THOUGHT. SO PRICE FEEDBACK HAS TOLD US THAT WE MUST USE R&D TO BRING CAPITAL AND OPERATING COSTS DOWN THROUGH DEVELOPING SYNTHETICS TECHNOLOGIES ADAPTABLE TO LOCAL CONDITIONS, RESOURCES, AND MARKETS. IN THE PROCESS, AS I SUGGESTED EARLIER, WE WILL CERTAINLY SUCCEED IN INCREASING THEIR EFFICIENCY AND SO REDUCING CO_2 EMISSIONS. IN THE CRUCIAL CONVERSION STEP, MANY OF TODAY'S SYNTHETICS TECHNOLOGIES OPERATE AT EFFICIENCES IN THE RANGE OF 60 PERCENT. BY THE YEAR 2000 WE SEE POSSIBILITIES FOR STEPPING UP THOSE EFFICIENCIES TO NEARLY 80 PERCENT. AND THIS IS NOT A FUNDAMENTAL LIMIT.

EXXON IS WORKING ON A VERY WIDE VARIETY OF SYNTHETICS OPTIONS, INCLUDING ADVANCED SHALE RETORTING AND DIRECT COAL LIQUEFACTION; A CATALYTIC PROCESS FOR PRODUCING METHANE DIRECTLY FROM COAL; THE GENERATION OF CO AND HYDROGEN, OR SYNTHESIS GAS, FROM COAL, LIGNITE, OR REMOTELY LOCATED NATURAL GAS; AND THE CONVERSION OF SYNTHESIS GAS TO FUELS AND CHEMICALS. ON THE NON-FOSSIL FUEL SIDE, EXXON HAS FOR MANY YEARS BEEN DOING R&D AIMED AT IMPROVING THE FABRICATION OF NUCLEAR FUEL ELEMENTS; AND WE HAVE BEEN ONE OF SEVERAL COMPANIES IN THE RACE TO PRODUCE CHEAPER SOLAR VOLTAIC CELLS MADE FROM AMORPHOUS SILICON.

These efforts suggest primarily the early stages of the transition. For the later stages, some interesting options are beginning to present themselves. A prime difficulty with synthetics resources is their high carbon content Chemically, that means low ratio of hydrogen to carbon. While the ratio is about four to one in natural gas and 1.8 in crude oil, it is only about 1.5 in oil sands bitumen or raw shale oil, and less than one in coal. In simple terms, a result is that producing these fuels means generating larger amounts of CO_2 than to produce comparable fuels from petroleum. Synfuels require more processing to manufacture and hence more processing heat generated by burning part of the resource.

Prompted by concerns about CO_2 emissions, among other things, some people have suggested a hydrogen economy, a fuel cycle based on hydrogen generated from water not using heat generated by fossil fuels. Perhaps there are ways to generate cheap hydrogen which could then feed directly into a synthetics process. One possible method would be to use thermochemical processes to split water, with advanced solar collectors or nuclear reactors supplying the process heat. The IIASA study notes that in manufacturing coal synthetics such a scheme would cut CO_2 emissions by <u>one-fourth to one-third</u>, compared to the usual coal conversion technologies envisioned. If they could generate hydrogen cheaply, such technologies would also cut overall costs sharply. For example, in the Exxon Donor Solvent coal liquefaction process, hydrogen accounts for well over a <u>third</u> of of the total cost of producing coal liquids.

Summary and Conclusion

To sum up, the world's best hope for inventing an acceptable energy transition is one that favors multiple technical approaches subject to correction--feedback from markets, societies, and politics, and scientific feedback about external costs to health and the environment. This approach is not easy, or comforting to the uninitiated, because there is no overall neat and understandable plan. But prophecies leading to masterminded solutions that commit a society unalterably to a single course are likely to be dangerous and futile. A good sign is that, without any central plan, the world economy has already adopted conservation technologies that are reducing the rate of CO_2 buildup.

In shaping strategies for energy research and development, we must recognize that, generally, societies will give primacy to economic growth, to least-cost energy alternatives, and, in most transportation uses, to liquid fuels. Fortunately, these conditions give science and engineering a lot of room to maneuver. It appears we still have time to generate the wealth and knowledge we will need to invent the transition to a stable energy system.

I hope I do not appear too sanguine about the collective wisdom of our species. History bears ample testimony to the human capacity for grievous folly, as well as achievement and excellence. Clearly, there is vast opportunity for conflict. For example, it is more than a little disconcerting

THAT THE FEW MAPS SHOWING THE LIKELY EFFECTS OF GLOBAL WARMING SEEM TO REVEAL THE TWO SUPERPOWERS LOSING MUCH OF THE RAINFALL, WITH THE REST OF THE WORLD SEEMINGLY BENEFITTING. AN ACCEPTABLE FUTURE MAY REQUIRE A DEGREE OF INTERNATIONAL COOPERATION THAT HAS ELUDED OUR GRASP TO DATE. AN EXCEPTION IS OF COURSE SCIENCE ITSELF AND IN PARTICULAR CLIMATOLOGY, WHICH EVEN BY THE STANDARDS OF SCIENCE HAS BEEN DISTINGUISHED BY A REMARKABLE DEGREE OF INTERDISCIPLINARY AND INTERNATIONAL COOPERATION. AS THE WORLD CONTINUES TO GRAPPLE WITH THE PROFOUND ISSUES POSED BY THE CO_2 BUILDUP, IT COULD SEEK FEW BETTER MODELS OF INTERNATIONAL COOPERATION THAN WHAT YOU HAVE ALREADY ACHIEVED.

######

EXHIBIT 23

CO$_2$

GENERAL 7A

MEMORANDUM

TO T. K. Kett

FROM HENRY SHAW

DATE December 18, 1980

Attached is the "CO_2 Greenhouse Effect" technological forecast. I have added the items you suggested on 12/16/80. Pat McCall has not had a chance to review this draft. He will contact you directly if he has any comments.

Henry

Henry

HS/lw

Attachment

cc: P. P. McCall
H. C. Hayworth
H. N. Weinberg

Exxon Research and Engineering Company's Technological Forecast

CO_2 Greenhouse Effect
by
H. Shaw and P. P. McCall

Current Status

The build-up of CO_2 in the atmosphere has been monitored continuously at the National Oceanic and Atmospheric Administration's Observatory at Mauna Loa, Hawaii and periodically in other places since 1957. In addition to observing a trend between 1957-1979 that showed atmospheric CO_2 increasing from 315 to 337 ppm, Keeling and others also observed a seasonal variability ranging from 6 to 10 ppm between a low at the end of summer growing season (due to photosynthesis) and a high at the end of the winter (due to fossil fuel burning for heat, and biomass decay). There is little doubt that these observations indicate a growth of atmospheric CO_2 (See Figure 1). It is also believed that the growth of atmospheric CO_2 has been occuring since the middle of the past century i.e., coincident with the start of the Industrial Revolution. There is, however, great uncertainty on whether the atmospheric CO_2 concentration prior to the Industrial Revolution was 290-300 ppm or 260-270 ppm.

The relative contributions of biomass oxidation (mainly due to deforestation) and fossil fuel combustion to the observed atmospheric CO_2 increase are not known. There are fairly good indications that the annual growth of atmospheric CO_2 is on the order of 2.5 to 3.0 Gt/a of carbon and the net quantity of carbon absorbed by the ocean is similarly 2.5 to 3 Gt/a. Thus, these two sinks (atmosphere and ocean) can account for the total fossil carbon burned which is on the order of 5-6 Gt/a and does not allow much room for a net contribution of biomass carbon. Yet, highly respected scientists, such as Woodwell, Bolin and others have postulated a net biomass contribution to atmospheric CO_2 that range from 1 to perhaps 8 Gt/a of carbon. The rate of forest clearing has been estimated at 0.5 to 1.5%/a of the existing area. Forests occupy about $50 \times 10^6 km^2$ out of about $150 \times 10^6 km^2$ of continental land, and store about 650 Gt of carbon. One can easily see that if 1% of the worlds forests are cleared per year, then this could contribute 6.5 Gt of carbon to the atmosphere. Even if reforestation were contributing significantly to balancing the CO_2 from deforestation, the total carbon stored in new trees would be only a small fraction of the net carbon emitted. It should be noted, however, that the rate of forest clearing and reforestation are not known accurately at this time. If deforestation is indeed contributing to atmospheric CO_2, then another sink for carbon must be found and the impact of fossil fuel must be considered in the context of such a sink.

Figure 2, taken out of a recent DOE publication summarizes the fluxes and reserviors for the carbon cycle. Note that a deforestation flux of 0 to 2 Gt/a and a net flux to the oceans of 4 Gt/a are assumed. Thus, the carbon flux to the atmosphere is 6 Gt/a of fossil fuels, and 2 Gt/a deforestation, while 4 Gt/a returned to the ocean resulting in a 50% carbon retention rate in the atmosphere. One of the major objectives of the Exxon Research and Engineering Company project to measure CO_2 in the oceans using tankers is to clarify and quantify the role of the oceans as the ultimate sink for CO_2.

Projections of scientists active in the area indicate that the contribution of deforestation which may have been substantial in the past, will diminish in comparison to the expected rate of fossil fuel combustion in the future. A number of scientists have postulated that a doubling of the amount of carbon dioxide in the atmosphere could occur as early as 2035. Calculations recently completed at Exxon Research indicate that using the energy projections from the CONAES study and the World Energy Conference, a doubling of atmospheric CO_2 can occur at about 2060. If synthetic fuels are not developed, and fossil fuel needs are met by petroleum, then the atmospheric CO_2 doubling time would be delayed by about 5 years to 2065. It is now clear to most people working in the area that the doubling time will be much later in the future that previously postulated because of the decreasing rate of fossil fuel use.

Description of potential impact on weather, climate, and land availability

The most widely accepted calculations carried on thusfar on the potential impact of a doubling of carbon dioxide on climate indicate that an increase in the global average temperature of $3\pm1.5^{\circ}C$ is most likely. Such changes in temperature are expected to occur with uneven geographic distribution, with greater warming occuring at the higher latitudes i.e., the polar regions. This is due to the presumed change in the reflectivity of the Earth due to melting of the ice and snow cover (See Figure 3). There have been other calculations on a more limited scale by a number of climatologists which project average temperature increases on the order of $0.25^{\circ}C$ for a doubling of CO_2. These calculations are not held in high regard by the scientific community. Figure 4 summarizes the results presented in the literature on the possible temperature increase due to various changes in atmospheric CO_2 concentration.

The area of climate modeling was recently studied by a committee of the National Research Council, chaired by Jules G. Charney of MIT, and the conclusions are summarized in their booklet titled "Carbon Dioxide and Climate: A Scientific Assessment." This National Research Council study concluded that there are major uncertainties in these models in terms of the timing for a doubling of CO_2 and the resulting temperature increase. These uncertainties center around the thermal

capacity of the oceans. The oceans have been assumed to consist of a relatively thin, well mixed surface layer averaging about 70 meters in depth in most of the general circulation model, and that the transfer of heat into the deep ocean is essentially infinitely slow. The Charney panel feels, however, that the amount of heat carried by the deep ocean has been underestimated and the oceans will slow the temperature increase due to doubling of atmospheric CO_2. The Charney group estimated that the delay in heating resulting from the effect of the oceans could delay the expected temperature increase due to a doubling of CO_2 by a few decades.

Along with temperature increase, other climatological factors that are expected to occur will include uneven global distribution of increased rainfall, and increased evaporation. These disturbances in the existing global water distribution balance will have dramatic impact on soil moisture, and in turn, on agriculture. The state-of-the-art in climate modeling allows only gross global zoning while some of the expected results from temperature increase of the magnitude indicated are quite dramatic. For example, areas that 4,000 to 8,000 years ago in the Altithermal period (when the global average temperature was some $2^{o}C$ higher than present) were deserts, may in due time return to deserts. Conversely, some areas which are deserts now were formerly agricultural regions. It is postulated that part of the Sahara Desert in Africa was quite wet 4,000 to 8,000 years ago. The American Midwest, on the other hand, was much drier, and it is projected that the Midwest will again become drier should there be a temperature increase of the magnitude postulated for a doubling of atmospheric CO_2 (See Figure 5).

In addition to the effects of climate on the globe, there are some particularly dramatic questions that might cause serious global problems. For example, if the Antartic ice sheet which is anchored on land, should melt, then this could cause a rise in the sea level on the order of 5 meters. Such a rise would cause flooding in much of the U.S. East Coast including the state of Florida and Washington D.C. The melting rate of polar ice is being studied by a number of glaciologists. Estimates range for the melting of the West Antartica ice sheet from hundreds of years to a thousand years.

In a recent AAAS-DOE sponsored workshop on the environmental and societal consequences of a possible CO_2 induced climate change, other factors such as the environmental effects of a CO_2 growth rate on the less managed biosphere were studied. For example, the impact of a temperature increase and a higher atmospheric CO_2 concentration on weeds and pests was considered. The general concensus was that these unmanaged species would tend to thrive with increasing average global temperature. The effects of atmospheric CO_2 growth on the managed biosphere such as in agriculture would also tend to benefit from a CO_2 growth. It turns out that CO_2 can fertilize agriculture, provided the other key nutrients, phosphorous and nitrogen, are present in the right proportions. Agri-

cultural water needs can be met by new irrigation techniques that require less water. In addition, with highest CO_2 and higher temperature conditions, the amount of water that some agricultural plants may need will be reduced. It is expected that bioscience contributions could point the way for dealing with climatological disruptions of the magnitude indicated above.

In terms of the societal and institututional responses to an increase in CO_2, it was felt that society can adapt to the increase in CO_2 and that this problem is not as significant to mankind as a nuclear holocaust or world famine. Finally, in an analysis of the issues associated with economic and geopolitical consequences, it was felt that society can adapt to a CO_2 increase within economic constraints that will be existing at the time. Some adaptive measures that were tested, for example, would not consume more than a few percent of the gross national product estimated in the middle of the next century.

Major Programs Underway

The DOE which is acting as a focal point for the U.S. government in this area is considering two reports to the scientific community and to the policy makers. The first one, summarizing five years of study is due in 1984, and the second one in 1989. The current plan is to spend approximately 10 years of research and assessment prior to recommending policy decisions in this area which impact greatly on the energy needs and scenarios for the U.S. and the world. The national program on CO_2, environment and society is summarized in Figure 6.

Projections on When General Concensus Can be Reached

It is anticipated by most scientists that a general concensus will not be reached until such time as a significant temperature increase can be detected above the natural random temperature fluctuations in average global climate. The earliest that such discreet signals will be able to be measured is after the year 2000. However, depending on the actual global energy demand and supply, it is possible that some of the concerns about CO_2 growth due to fossil fuel combustion will be minimized if fossil fuel use is decreased due to high price, scarcity, and unavailability. Figure 7 illustrates the behavior of the mean global temperature from 1850 to the present contained within an envelope scaled to include the random temperature fluctuations.

Future Scenarios and Their Consequences For Exxon

A number of future energy scenarios have been studied in relation to the CO_2 problem. These include such unlikely scenarios as stopping all fossil fuel combustion at the 1980 rate, looking at the delay in doubling time and maintaining the pre-1973 fuel growth rate. Other studies have investigated the market penetration of non-fossil fuel

technologies such as nuclear, and its impact on CO_2. It should be noted, however, that a new technology in a competitive scenario would need about 50 years to penetrate and achieve roughly half of the total market. Thus, even if solar or nuclear were to be considered viable alternatives, these would not really displace fossil fuel power generation for the next 50 years or so, and CO_2 growth would have to be estimated based on realistic market displacement of the fossil fuel technologies. All of these studies tend to give a range of deviations on the order of 50 years, indicating a CO_2 doubling time that might be as early as 2035 (for a fossil fuel growth rate of 4.3%), to a doubling time occuring by about 2080 resulting from scenarios which assumed fossil fuel growth rates of 1 to 2%. Synthetic fuels will cause minor perturbations on the projected atmospheric CO_2 growth rates in the next century.

FIGURE 1

Trend in Atmospheric CO_2 Concentrations at Mauna Loa (Hawaii)

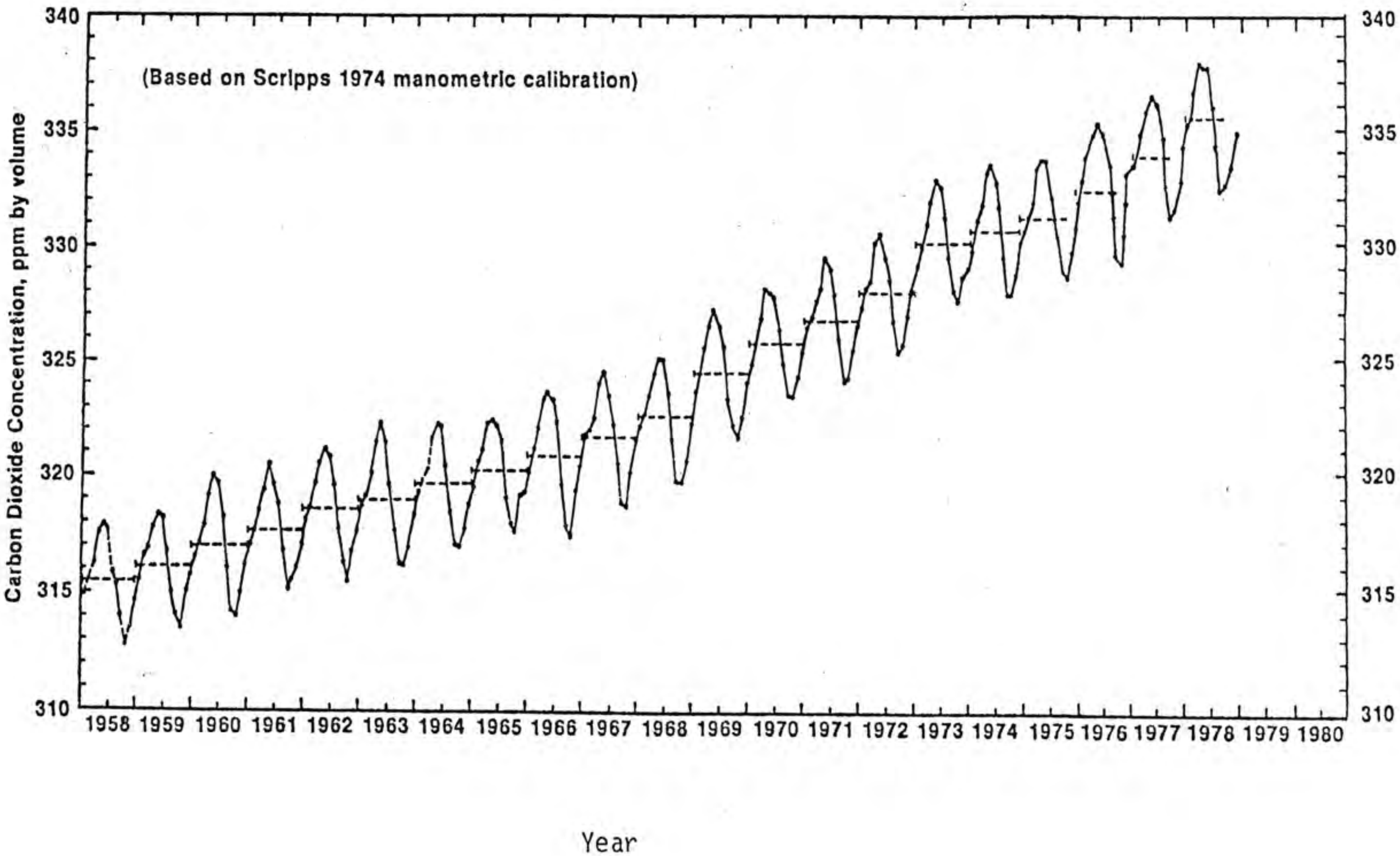
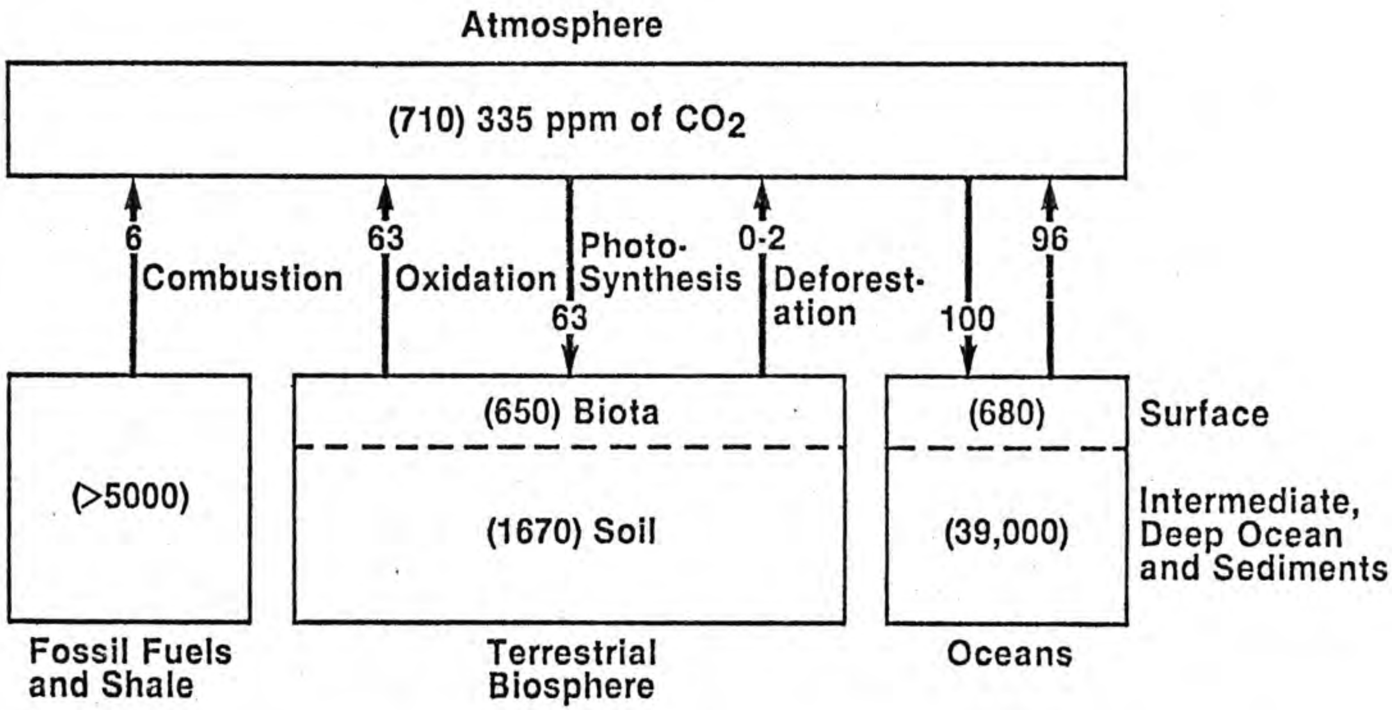


FIGURE 2

Exchangeable Carbon Reservoirs and Fluxes

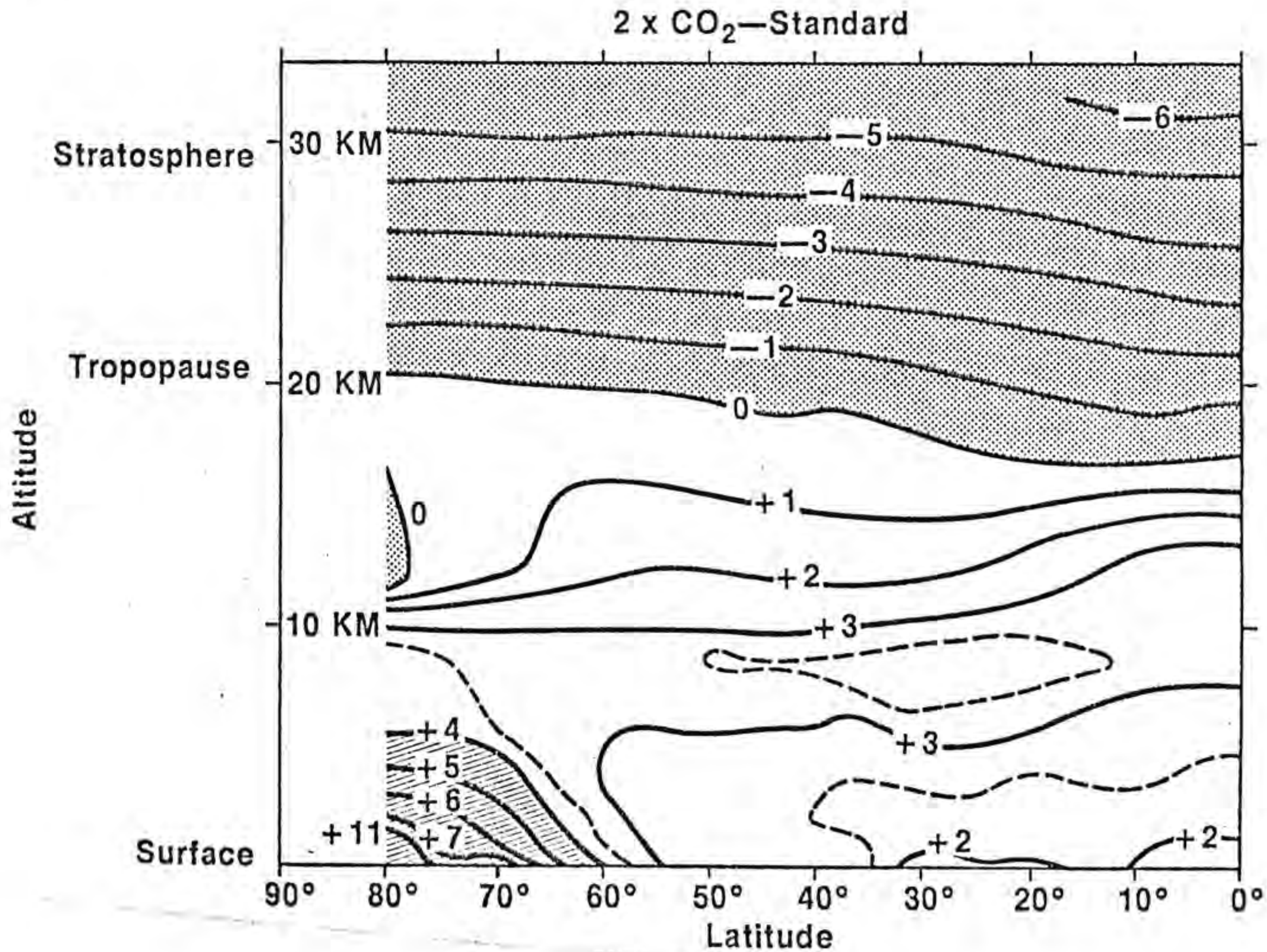


( ) = Size of Carbon Reservoirs in Billions of Metric Tons of Carbon

Fluxes (arrows) = Exchange of Carbon Between Reservoirs in Billions of Metric Tons of Carbon per Year

FIGURE 3

Temperature Change (°C) Due to Doubling CO_2 Concentrations



---- Decrease in Temperature

FIGURE 4

Estimates of the Change in Global Average Surface Temperature Due to Various Changes in CO_2 Concentration. Shading Shows Present Range of Natural Fluctuations.

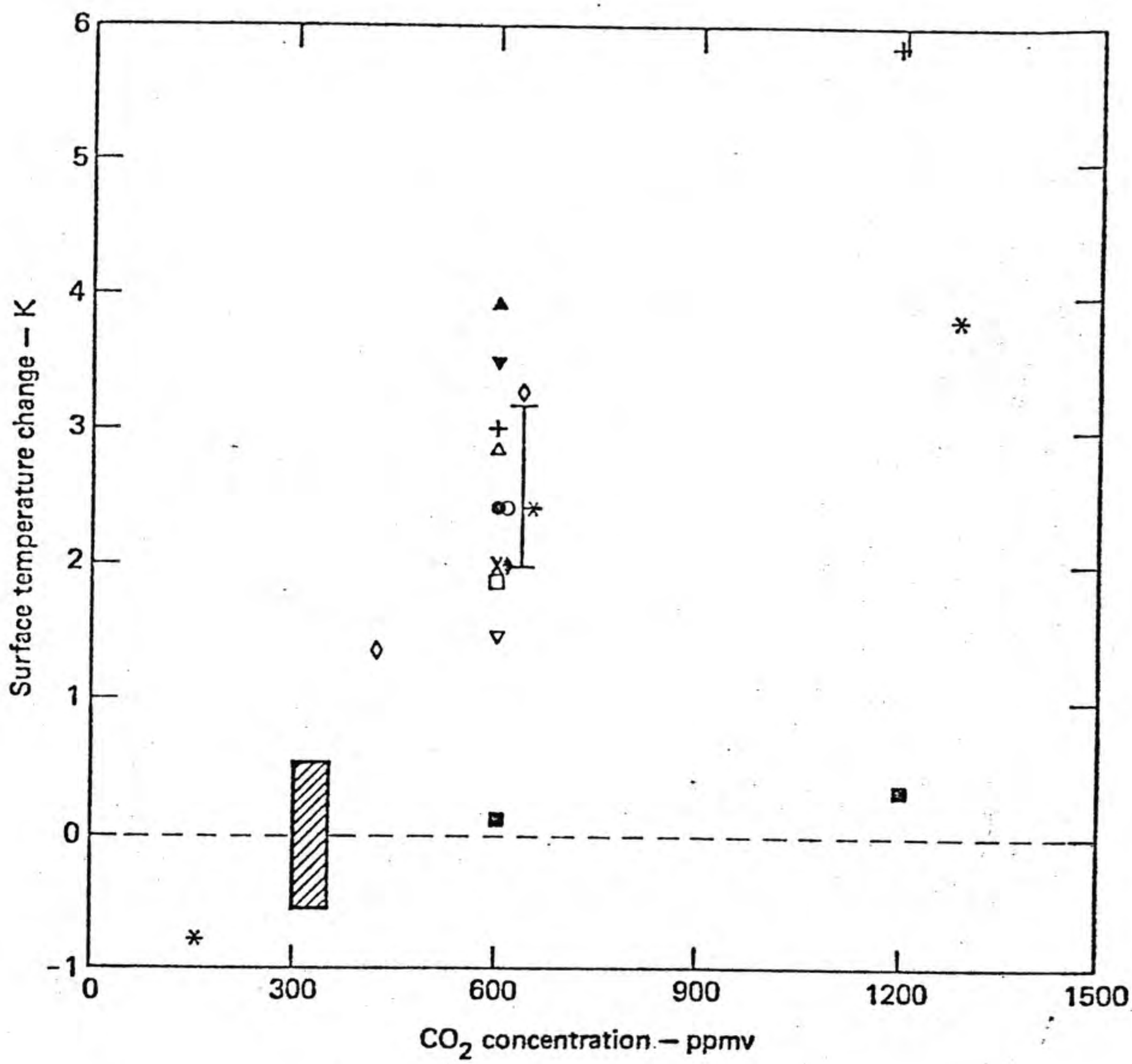


FIGURE 5

The Altithermal Period

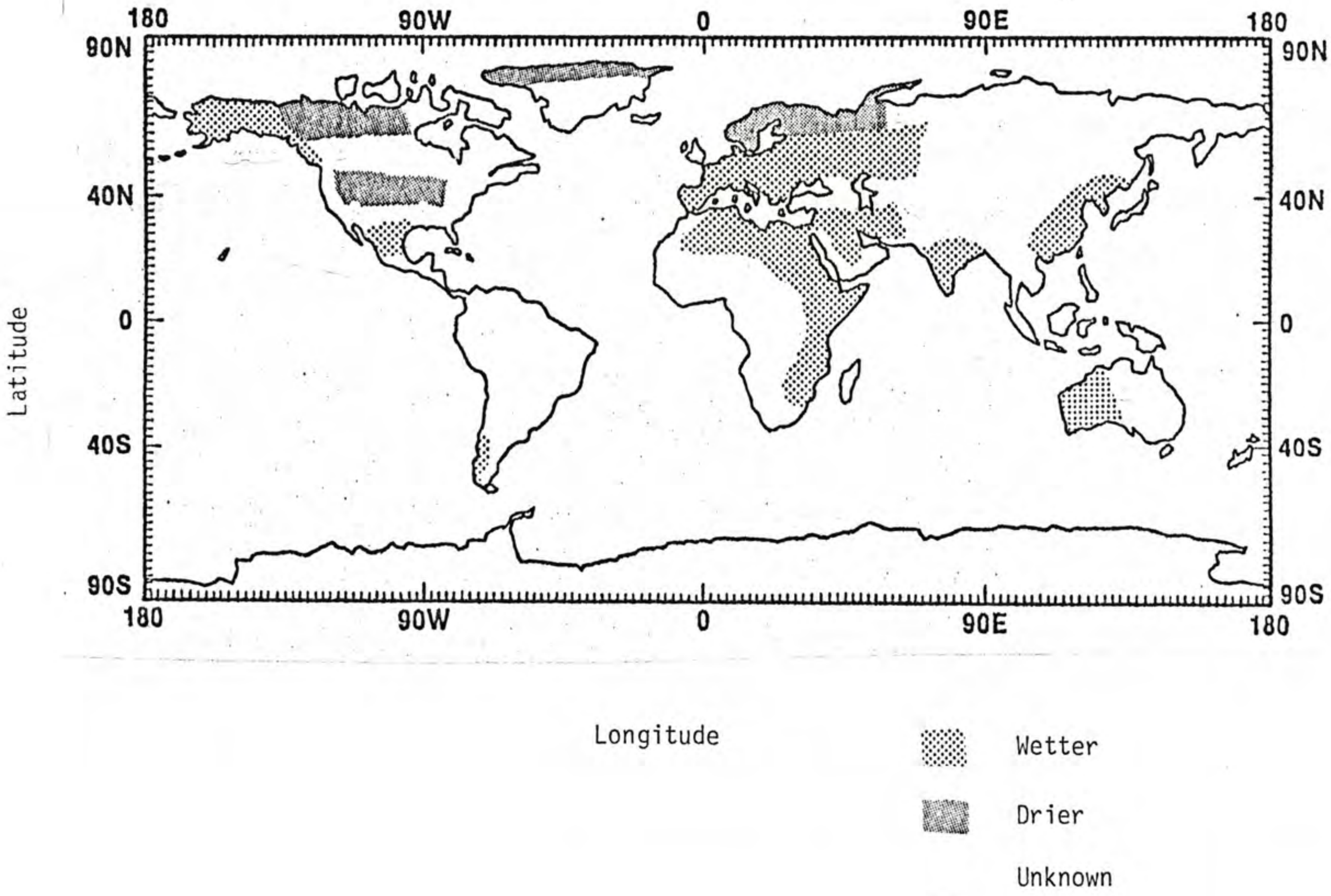


FIGURE 6

A National Program on Carbon Dioxide, Environment and Society

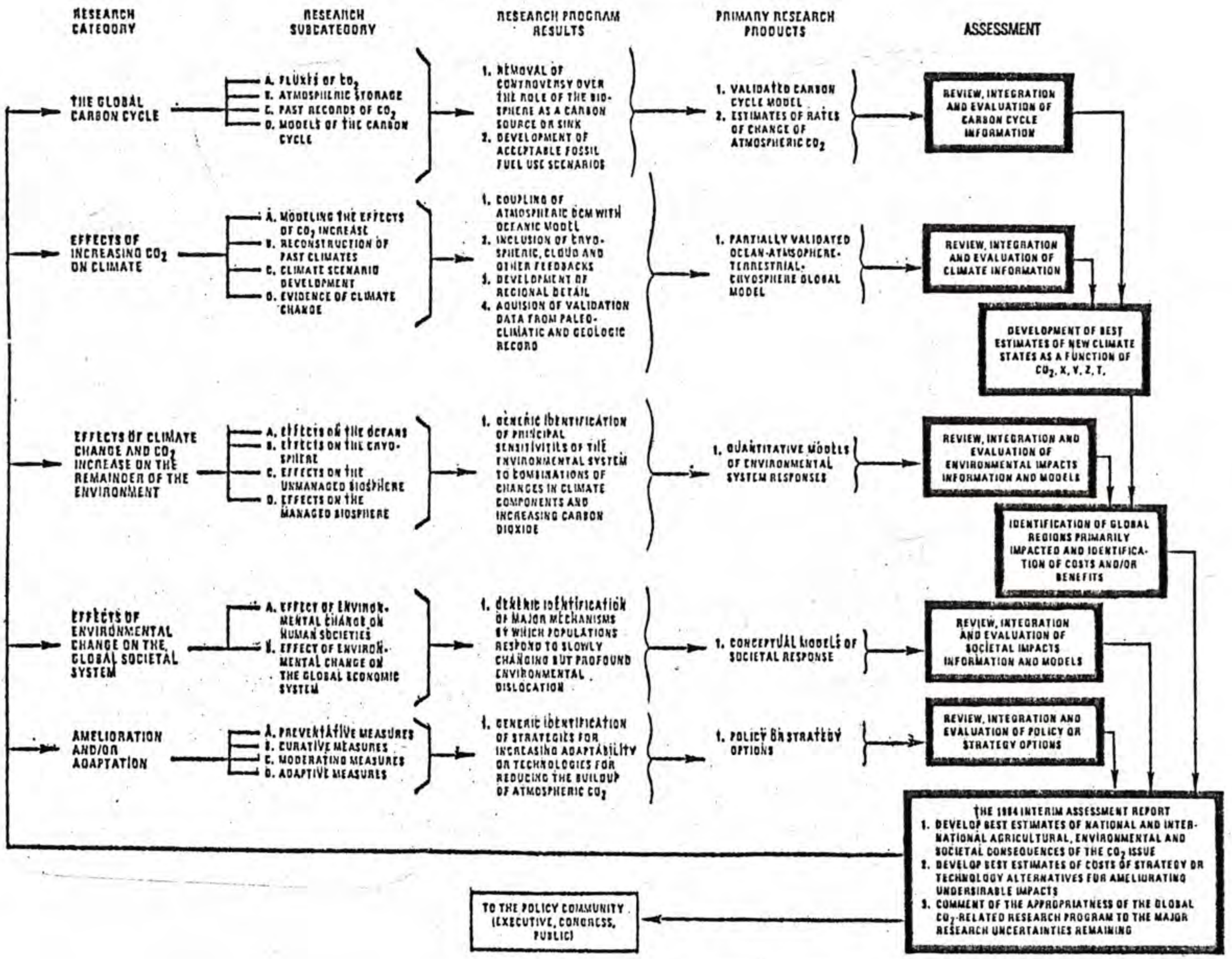


FIGURE 7

Range of Global Mean Temperature From 1850 to the Present with the Projected Instantaneous Climatic Response to Increasing CO_2 Concentrations.

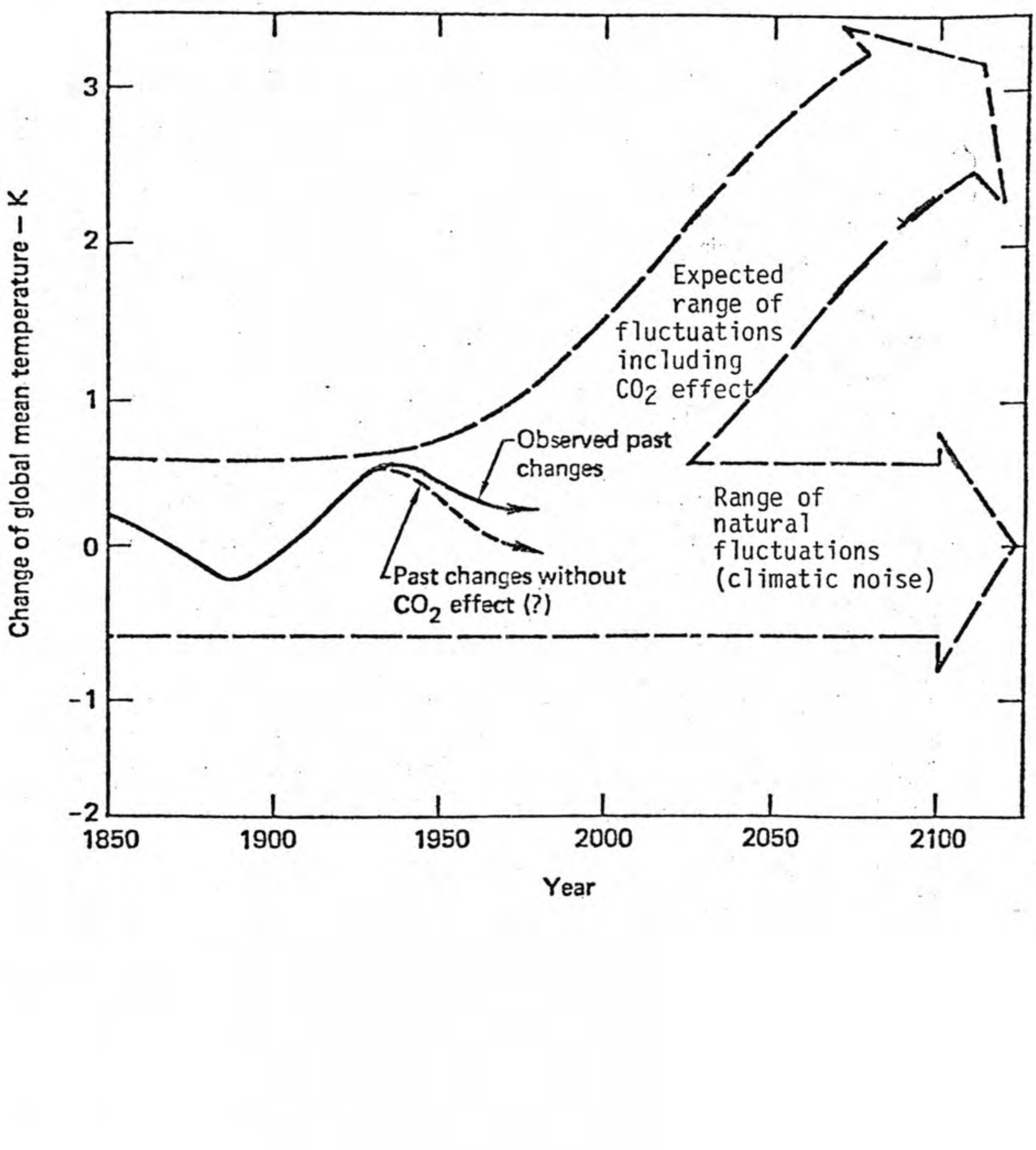


EXHIBIT 24

Report Series HSE 88-001

CONFIDENTIAL

THE GREENHOUSE EFFECT

SHELL INTERNATIONALE PETROLEUM MAATSCHAPPIJ B.V., THE HAGUE

Health, Safety and Environment Division (HSE)

Report Series HSE 88-001

CONFIDENTIAL

THE GREENHOUSE EFFECT

SHELL INTERNATIONALE PETROLEUM MAATSCHAPPIJ B.V., THE HAGUE

Health, Safety and Environment Division (HSE)

CONFIDENTIAL

THE GREENHOUSE EFFECT

Greenhouse effect working group
R.P.W.M. Jacobs HSE/35

M.H. Griffiths PL/15
P.E. Bright PAC/3
J.B. Homer SCCU
J.A.C.M. van Oudenhoven MFPA/435
J. Waller MFPA/435

Shell Internationale Petroleum Maatschappij B.V.
Health, Safety and Environment Division
Environmental Affairs
The Hague

April 1986 (completion of the study)
May 1988 (date of issue in this format)

Prepared for SECC
(Shell Environmental Conservation Committee)

SUMMARY

Man-made carbon dioxide, released into and accumulated in the atmosphere, is believed to warm the earth through the so-called greenhouse effect. The gas acts like the transparent walls of a greenhouse and traps heat in the atmosphere that would normally be radiated back into space. Mainly due to fossil fuel burning and deforestation, the atmospheric CO_2 concentration has increased some 15% in the present century to a level of about 340 ppm. If this trend continues, the concentration will be doubled by the third quarter of the next century. The most sophisticated geophysical computer models predict that such a doubling could increase the global mean temperature by 1.3-3.3°C. The release of other (trace) gases, notably chlorofluorocarbons, methane, ozone and nitrous oxide, which have the same effect, may amplify the warming by predicted factors ranging from 1.5 to 3.5°C.

Mathematical models of the earth's climate indicate that if this warming occurs then it could create significant changes in sea level, ocean currents, precipitation patterns, regional temperature and weather. These changes could be larger than any that have occurred over the last 12,000 years. Such relatively fast and dramatic changes would impact on the human environment, future living standards and food supplies, and could have major social, economic and political consequences.

There is reasonable scientific agreement that increased levels of greenhouse gases would cause a global warming. However, there is no consensus about the degree of warming and no very good understanding what the specific effects of warming might be. But as long as man continues to release greenhouse gases into the atmosphere, participation in such a global "experiment" is guaranteed. Many scientists believe that a real increase in the global temperature will be detectable towards the end of this century or early next century. In the meanwhile, greater sophistication both in modelling and monitoring will improve the understanding and likely outcomes. However, by the time the global warming becomes detectable it could be too late to take effective countermeasures to reduce the effects or even to stabilise the situation.

The likely time scale of possible change does not necessitate immediate remedial action. However, the potential impacts are sufficiently serious for research to be directed more to the analysis of policy and energy options than to studies of what we will be facing exactly. Anticipation of climatic change is new, preventing undue change is a challenge which requires international cooperation.

With fossil fuel combustion being the major source of CO_2 in the atmosphere, a forward looking approach by the energy industry is clearly desirable, seeking to play its part with governments and others in the development of appropriate measures to tackle the problem.

CONTENTS

FIGURES

TABLES

APPENDICES

1. INTRODUCTION

The life-supporting systems of the earth (such as light, energy, moisture, and temperature) can be affected by changes in global conditions. Many of such changes are occurring at present, some of them subtle and many of them caused by man. These effects on the life-supporting systems can have a substantial impact on global habitability. The rate at which many of these changes are occurring, especially during the past few decades, has been considerable. A obvious example of this is the rising level of atmospheric carbon dioxide (CO_2). This has been described as a long-term global experiment, the outcome of which is very uncertain.

The global rise in atmospheric CO_2 is well documented. It is estimated that human activities (e.g. fossil fuel burning, deforestation) have increased the CO_2 concentration by about 15% during the past century. More than a century ago it was already hypothesised that an increase in the CO_2 concentration of the atmosphere would lead to global warming, i.e. the so-called "greenhouse effect". Several other gases, having similar effects, also appear to be increasing as a result of human activities.

Many scientists believe that the major effect of increasing the CO_2 content of the atmosphere will be a gradual warming of the earth's surface. Should average global temperatures rise significantly because of the greenhouse effect and should the earth's climate change, this could have major economic and social consequences. However, not everyone agrees with this view of possible disaster. They point to the demonstrable positive effects of elevated CO_2 concentrations, and suggest a benefit to the biosphere without the generation of a climatic catastrophe. Against this backlog of disagreement scientists of both persuasions have searched for the first signs of any effects on a global scale.

It is estimated that any climatic change relatable to CO_2 would not be detectable before the end of the century. With the very long time scales involved, it would be tempting for society to wait until then before doing anything. The potential implications for the world are, however, so large that policy options need to be considered much earlier. And the energy industry needs to consider how it should play its part.

In this report the latest (1986) state of knowledge is presented regarding the greenhouse effect to judge any counteractive measures. It describes the considerable research work being carried out world wide; it provides information to improve the understanding and it discusses the implications. For this reason additional information is added on legislation and policies (Appendix 3), relevant international organisations and information centres (Appendix 5) and institutes involved in greenhouse effect research (Appendix 6). Moreover, in addition to the references used, a list of relevant reports and books is added (Appendix 7) to provide the interested reader access to the enormous flow of information relative to the greenhouse effect.

References used in this section: 2, 14, 21, 25, 51, 59.

2. SCIENTIFIC DATA

2.1. Introduction

During the last century the concentration of carbon dioxide increased from an estimated 290 ppm in 1860 to 340 ppm in 1980. Approximately 25% of this increase occurred during the 1970s. Although the concentration of CO2 in the atmosphere is relatively small, it is important in determining the global climate. It permits visible and ultraviolet radiation from the sun to penetrate to the earth's surface, but absorbs some of the infrared energy that is radiated back into space. The atmospheric CO2 emits this energy to both the troposphere and to the earth's surface (see Fig. 1), resulting in a warming of the surface and the atmosphere in the way the glass in a greenhouse does - hence the term greenhouse effect.

The best known and most abundant greenhouse gas is carbon dioxide. However, some trace gases, particularly chlorofluorocarbons (CFC's), ozone, methane, and N2O are at least as important in changing the radiation energy balance of the earth-atmosphere system, as, collectively, they might cause an additional warming equal to 50-100% of the warming due to CO2 alone.

It has been generally accepted that any modification in the radiation energy balance of the atmosphere will affect the global circulation patterns. As a consequence regional climatic changes will then occur, which will be greater than the average global changes. The most promising approach to study the effects of increasing gas concentrations on the atmosphere, is to describe and predict the (future) global climate by complex General Climate Models (GCM's). The main factors and processes used to predict the earth's temperature profiles and climatic changes are presented in this section. The extent and rate of the changes, based on scenarios for energy consumption and emission of CO2 and other trace gases, will be discussed in section 3.

2.2. Data on emissions of greenhouse gases

2.2.1. Carbon dioxide

Although CO2 is emitted to the atmosphere as a consequence of several processes, e.g. oxidation of humic substances and deforestation, the main cause of increasing CO2 concentrations is considered to be fossil fuel burning. Only fossil fuel burning can be fairly accurately quantified.

Since the beginning of the industrial and agricultural revolutions the average annual increase in CO2 production has been 3.5%, with total emissions from mid-nineteenth century to 1981 being 160 GtC (1 GtC=1 gigaton of carbon = 10^{15} g C). In 1860 the annual emission was approximately 0.093 GtC and in 1981 5.3 GtC. Rising fuel prices in the 1970's slackened the CO2 production to yearly increases of 2.2% per year over the period 1973-1980 (see the first part of Fig. 2).

The CO2 emitted into the atmosphere is very quickly globally distributed. This is mainly due to the fact that the emissions are more or less evenly distributed over the continents. Moreover, the mixing time of the atmosphere within a hemisphere is only a few weeks and the interchange between the hemispheres takes 6-12 months. CO2 has a residence time in the atmosphere of 3-4 years, so is reasonably well mixed globally.

World CO_2 emissions based on energy growth rates (see Table 1) show that there has been a slowing in the upwards growth of emissions since 1973. In 1981, of the total emission of 5.3 GtC 44% came from oil, 38% from coal, and 17% from gas.

The production of CO_2 differs considerably from country to country. The largest quantities (based on 1975 figures) are produced in the developed countries with a world average of 1.2 tonnes C per person (see Table 3).

During the last century the concentration of carbon dioxide in the atmosphere increased from an estimated 290 ppm in 1860 (measurements from ice cores) to 340 ppm in 1980. More accurate measurements over the last 25 years at the Mauna Loa Observatory, Hawaii, show an average increase of 1.5% per year (see Fig. 4) with season-dependent fluctuations. Moreover, there is a latitudinal difference between ground-level CO_2 concentrations, reflecting the location of the main fossil fuel CO_2 sources in the northern hemisphere (see Fig. 5). The hypothetical increase of the atmospheric CO_2 concentration based on emissions due to fossil fuel burning, is also given in Fig. 4. It appears that only a proportion of the emission is retained in the atmosphere (i.e. the "airborne fraction", AF). The size of AF depends on how the total carbon inventory is partitioned among the oceanic, terrestrial and atmospheric pools. Over the period 1959-1974 the AF was 56%, whereas it was 59% for the period 1975-1980. It is assumes that this increase of AF might be a caused by a reduction of the absorption capacity of the oceans.

References used in this chapter: 1, 5, 18, 20, 30, 44, 54, 69.

2.2.2. Other greenhouse gases

The earth's atmosphere currently contains "trace gases" with atmospheric lifetimes that vary from much less than an hour to several hundred years (see Table 4). From a viewpoint of global climate effects, species with extremely short lifetimes are unlikely to play an important direct role. More persistent trace gases, however, may contribute to modifications of the energy balance of the earth-atmosphere system and amplify the estimated CO_2 warming. Increasing concentrations of these gases are directly or indirectly a consequence of human activities. Most of the man-made trace gases are listed in Table 4; the most important ones are briefly discussed below.

Nitrogen compounds

While a number of nitrogen containing compounds are relevant from a climatic point of view, the most important is N_2O. N_2O emissions result primarily from biological denitrification processes in soil and in the oceans. The global atmospheric concentration of N_2O has risen from an estimated pre-industrial value of 285 ppb to 301 ppb in 1980. Over the 4-year period 1976-1980 the rate of increase in N_2O concentration was 0.2% per year. Increasing future global food production will require increasing use of fertilisers adding further to atmospheric N_2O.

Methane

Principal sources of atmospheric methane are enteric fermentation in ruminant animals, anaerobic decomposition of organic matter (e.g. release from organic-rich sediments below water bodies and rice paddies), biomass decomposition, natural gas leakage, quite possibly production by termites and release of methane during mineral, oil, and gas exploration and gas transmission. The CH_4 concentration has approximately doubled in the last 350 years with a greater rate of increase in the last century. The concentration increased globally by about 0.5% per year between 1965 and 1975 and by 1-2% per year between 1978 and late 1980. In 1980 the concentration was about 1.65 ppm in the northern hemisphere, and about 6% lower in the southern hemisphere.

In the troposphere the CH_4 oxidation chain initiated by the reaction with hydroxyl radical (OH) leads to significant photochemical production of CO, H_2 and O_3:

$$CH_4 + 4O_2 \longrightarrow H_2O + CO + H_2 + 2O_3 \text{ (net cycle)} \qquad (1)$$

The initial reaction of OH with CH_4:

$$CH_4 + OH \longrightarrow CH_3 + H_2O \qquad (2)$$

and the reaction of OH with CO:

$$CO + OH \longrightarrow CO_2 + H \qquad (3)$$

controls the global destruction of OH, the dominant oxidising species in the troposphere. Reaction (2) is such a dominant loss mechanism for CH_4 that more than 90% of the global destruction of CH_4 occurs in the troposphere. So, CH_4 and CO are closely coupled photochemically through OH. The dominant sink of atmospheric CH_4, OH, is thus affected by increased levels of tropospheric CO or of CH_4 itself. Therefore, increasing concentrations of CO due to fossil fuel (incomplete combustion) usage and oxidation of anthropogenic hydrocarbons in the atmosphere , will reduce the rate at which CH_4 is destroyed.

Chlorofluorocarbons

Chlorofluorocarbons (CFC's) are entirely a product of human activity, being present in gas propelled spray cans, refrigeration equipment and insulated packaging materials. These chemicals came into major use in the 1960's and initially exhibited a rapid growth (10-15% per year). The global emissions of the major CFC's then declined somewhat from the mid-1970's through to 1982 in part due to a ban on some nonessential usages (e.g. spray cans) of CFC's and to adverse economic conditions. However, the emissions increased significantly since 1983. Eastern block countries have apparently never reduced their production of CFC's, so world wide use is now rising, and is expected to grow more because of the use in less industrialised countries. When CFC's are released to the atmosphere, their inertness to most biological processes allows them to be transported to the stratosphere, where they are broken down by sunlight. Liberated chlorine catalytically destroys ozone.

Ozone

The climatic effects of changes in ozone (O3) depend very strongly on whether these changes occur in the troposphere or stratosphere. There is some observational evidence that northern hemisphere tropospheric ozone has increased by 0.8-1.5% per year since about 1967, due to increases in combustion releases of NOx, CO2, H2 and increased CH4. In the southern hemisphere, given the smaller anthropogenic influences, O3 does not change at all.

Stratospheric ozone is also thought to be susceptible to perturbing influences, including man-made chloro- and chlorofluorocarbons, increasing CH4 and N2O concentrations and decreases in stratospheric temperature due to increasing CO2. The stratospheric ozone changes largely depend on the altitude, but concentrations are now about 12.5% greater at altitudes from 0 to 12 km than assumed pre-industrial concentrations.

A perturbation of the stratospheric ozone concentrations modulates the solar and infrared fluxes to the troposphere, and this solar effect would tend to warm the surface. On the other hand O3 changes in the lower atmosphere pose potential risks to air quality over the surface of the globe.

References used in this section: 33, 35, 39, 41, 43, 46, 47, 49, 61, 64.

2.3. <u>The global carbon cycle</u>

The carbon cycle (Fig. 6) involves numerous biological, geological, physical and chemical processes and can roughly be divided into two main cycles, a biological and a geological one. The geological cycle is a relatively long-term cycle characterised by slow processes, i.e. the release of CO2 through rock weathering and ultimate precipitation as calcium carbonate. Since man started to burn fossil fuel the slow processes have been unbalanced by affecting the major reservoir.

The worldwide use of fossil fuel in 1981 released about 5.3 GtC to the atmosphere as CO2. This figure seems very small compared to those of the amounts of carbon estimated to be present as organic and inorganic compounds in the four major reservoirs in the carbon cycle, i.e. 700 GtC in the atmosphere, 2,600 GtC in the biosphere, 40,000 GtC in the ocean and 65×10^6 GtC in the lithosphere (i.e. the solid part of the earth). However, taking into account a natural and balanced exchange rate of about 100 GtC per year between atmosphere and biosphere and between atmosphere and ocean, fossil fuel burnt yearly represents about 5% of the natural exchange. About 60% of the CO2 originating from burnt lithospheric carbon is retained in the atmosphere; the ocean is the major sink for the rest.

In contrast, the biological cycle is characterised by very rapid processes and is, in essence, very short and therefore extremely significant. Nearly all CO2 carbon that is assimilated (fixed) by the biosphere (i.e. the plants) is ultimately biodegraded by heterotrophic organisms and subsequently returns from the biosphere to the other major carbon reservoirs. The biological cycle is therefore essentially closed. Solar energy keeps the cycle going by providing the energy for the carbon-fixing process, i.e. photosynthesis.

Contrary to the near constancy of the fluxes in the biological cycle, one of the most important reservoirs therein (the land biota, i.e. the living organisms on land, of which the plants represent the major biomass) has been affected since man started releasing carbon dioxide by deforestation and expansion of arable land.

2.3.1 **Atmosphere - ocean interactions**

The reservoir of the world's oceans represents a volume of about 1.4×10^{18} m^3 water and holds about 40,000 GtC (this is about 57 times the total atmospheric carbon content) or on average 28 g/m^3. The content varies from 22 g/m^3 in cold surface water to 26 g/m^3 in warm surface water and to 29 g/m^3 in the deep-ocean.

The majority of the carbon in the ocean is present as an inorganic fraction, i.e. 39,000 GtC as dissolved inorganic carbon (DIC or C). The DIC is present as dissolved components of the carbon dioxide equilibrium system: CO2, bicarbonate and carbonate.

The remaining carbon is present as an organic fraction, of which only 1.5% is fixed in living organisms, and the rest is dead organic material present as dissolved organic carbon (DOC, about 1000 GtC), and particulate organic carbon (POC, about 30 GtC (see Fig. 6).

The gross exchange of CO2 between atmosphere and ocean is very rapid, characterised by a flux of about 100 GtC per year either way.
This interaction shows the strong regulation of the atmospheric CO2 by the ocean. The natural situation is characterised by a physico-chemical equilibrium. The principal effect of adding CO2 to the atmosphere is the tendency of the ocean to take up the excess in order to reach a new equilibrium with the atmosphere. Although the carbon content of the ocean is much greater than that of the atmosphere, the capacity of the ocean for CO2 uptake is limited (see Appendix 1). The absorption of CO2 by the ocean is buffered by reactions with dissolved carbonate and bicarbonate ions. In the surface mixed layer, the "buffer factor" increases with growing CO2 concentrations (see Fig. 7), and the capacity of the ocean to absorb the CO2 added to the atmosphere will decrease. Hence, the fraction of added CO2 remaining in the atmosphere will rise.

The capacity of the ocean for CO2 uptake is thus a function of its chemistry; the rate at which this capacity can be brought into play is, however, a function of ocean physics. The stratification of low- and mid-latitude oceans is stable and capped by a warm surface layer that is approximately in equilibrium with atmospheric CO2. Most of the deep waters of the world's oceans are formed in winter in the Norwegian and Greenland Seas and in the Weddell Sea. Here winter cooling increases the density of the surface waters until the stratification of the water column breaks down and the deep source regions are renewed. Once formed, the bottom waters flow to the south. The residence time of deep water in the Atlantic Ocean has been estimated as 275 years, in the Pacific Ocean about 600 years and in the Indian Ocean about 335 years. Thus, although the absorptive capability of the ocean is large, it is not rapid due to its slow circulation.

The cycle of organic carbon within the ocean is based on two main processes, i.e. production and decomposition of organic matter. Fixation of CO2 into

organic tissues by the photosynthetic activity of phytoplankton occurs only in ocean surface water (the euphotic zone). This is the zone where light energy for photosynthesis and growth is not limited, so that the production of organic material is greater than the breakdown. In the tropics this zone is limited to the upper 100 m of the sea, while in temperate climates it is between 20 and 50 m in summer and zero in winter. In deeper waters, the aphotic zone, there is a net loss of organic material, since breakdown exceeds production.

Organic production and breakdown of organic material can conveniently presented as:

$$CO2 + H2O \underset{\text{breakdown}}{\overset{\text{production}}{\rightleftharpoons}} CH2O + O2 \qquad (4)$$

CO2 in (4) represents the total dissolved inorganic carbon content of the water, and CH2O is organic matter. Oxygen is produced in this process and the removal of CO2 concurrently raises the pH. Although the total biomass of the biota is low relative to that on land (see Fig. 6) and the annual productivity is approximately one half that on land, the turnover (i.e. amount of carbon fixed per biomass unit) is very high. Some 90% of the organic matter formed is consumed by grazing organisms within the euphotic zone. The remainder plus the material excreted by grazing organisms and dead animals fall through the water column and is subject to oxidative decomposition (breakdown), whereby CO2 is released (eqn 4). The majority is decomposed in the upper 1000 m of the water column; dissolution of CaCO3 (i.e. calcium carbonate, the main constituent of shells) occurs in deeper water, stimulated by lowered oxygen concentration and pH due to increasing CO2 levels. The dissolved calcium carbonate raises the total CO2 of the deep water further and increases the alkalinity (see Appendix 1). The majority of the CO2 therefore remains available in the oceanic cycle.

<u>Effects</u> of increasing atmospheric CO2 on the CO2 concentration in the ocean are difficult to measure. The most sensitive measurement to determine this is pCO2 (i.e. the pressure of CO2 gas that would be found in a small volume of air that had been allowed to reach equilibrium with a large volume of seawater). From these measurements it is clear pCO2 in ocean surface water is rising, with a rate comparable to the atmospheric increase. However, as a consequence of the oceanic buffering a 10% change in pCO2 produces only a 1% change in the oceanic CO2 concentration (see Appendix 1 for details). The oceanic CO2 concentration has increased 1-2% over this last century. This increase will not induce significant changes in primary production (i.e. growth of algae), as CO2 is already available in excess. Concurrent slight decrease in pH (attached as 0.06 pH units) will not be measurable effect, as the ocean surface pH varies between 8.0 and 8.3. Further increases of the CO2 concentration will certainly lead to detectable effects on pH.

If the increasing atmospheric CO2 causes significant changes in the global climate, indirect effects on primary production can be expected. If there were to be locally increasing cloudiness then this reduces the solar energy reaching the ocean and consequently also the primary production. Any warming of the upper layers would increase the formation of stable water masses, thereby reducing vertical mixing. The subsequent depletion of nutrients in the euphotic zone will cause a decrease in primary production.

If CO_2 is added to the ocean surface, the pH decreases and the tendency for dissolution of carbonate minerals (e.g. calcite and aragonite), either in bottom sediments or suspended in the water column, increases, thereby increasing both the alkalinity and the total DIC (see also Appendix 1). However, $CaCO_3$ is also a major constituent of shells of calcareous organisms and corals. Particularly in near-shore areas these organisms will be exposed to waters rich in CO_2 and with a low pH. Dissolution of shells and corals and subsequently local but massive deaths of organisms on a local scale is therefore not unrealistic. If dissolution of carbonates occurs, the alkalinity and CO_2 content increase and the net effect of the alkalinity increase generates an increasing capacity of the ocean for CO_2 uptake. This feedback mechanism might have reducing effects on a rising atmospheric CO_2 level, although probably not in the short-term, as there are kinetic limits and controls on carbonate dissolution.

References used in this section: 3, 6, 7, 11, 22, 36, 42, 56, 60.

2.3.2. Atmosphere - terrestrial biosphere interactions

The reservoir of carbon in living plant material (phytomass) in the land biota was about 600 GtC in 1980. Compared to this, the organic carbon fixed in animals (zoomass) and microorganisms is negligibly small (about 8 GtC). The total carbon retained in soils and in dead organic material has been estimated globally at about 2000 GtC (see Fig. 6). The biosphere can be roughly subdivided horizontally into six ecosystems (see Table 5) and vertically into leaves, branches, stemwood, roots, litter, young humus and stable soil carbon. By far the largest biotic reservoir is estimated to be in forest systems, which are also both the most active and vulnerable part of the biota. The expansion of human populations and changes in land use in recent centuries have been accompanied by an almost continuous decline in the area of forest (see Table 5). During the past century the reduction in the mass of vegetation (deforestation) and replacement with agricultural crops and urban development resulted in a considerable reduction of the carbon stored in terrestrial biota. The total net release of carbon from the biota between 1860 and 1980 has been estimated as 180 GtC. In recent years the rate of release has dropped slightly, as a consequence of net accumulation of carbon in the forests of North America and Europe (as result of renewed growth of forests and afforestation).

The cycle of carbon between biosphere and atmosphere is in essence a biological one, based on fixation of CO_2 by plants with the aid of solar energy (i.e. photosynthesis) and production of CO_2 through respiration and decomposition (eqn 4). The driving input of an ecosystem is the net primary production, the increase in biomass (NPP):

$$NPP = GP - R_A \tag{5}$$

where GP is the gross production, the total photosynthesis of the system and R_A is the respiration of autotrophs, the green plants. Four, vertically arranged, components of the biosphere contribute to the NPP, i.e. leaves, branches, stems and roots. Estimates of NPP for the different ecosystems are given in Table 5.

The net flux of carbon between the atmosphere and any ecosystem is determined by the balance between gross production and respiration of all living organisms:

$$NEP = GP - (R_A + R_H) \qquad (6)$$

where NEP is the net ecosystem production, the net flux of carbon into or from an ecosystem and R_H is the respiration of the heterotrophs, including all animals and decomposers. Thus, $R_A + R_H$ represent the natural flux of CO_2 from the terrestrial ecosystems to the atmosphere. The primary evidence of the importance of the terrestrial biota for the CO_2 content of the atmosphere is shown by the short-term oscillations of atmospheric CO_2, reflecting the seasonal fluctuations in photosynthetic and respiratory activities of living organisms.

The NEP tends to be zero in a stable ecosystem, but is permanently positive when human disturbance is present. Estimates of the total NPP for all terrestrial ecosystems vary between 50-60 GtC per year; the mean total plant respiration of all ecosystems (R_A) is about equal to NPP; so, about 50% of GP is needed by the plants for respiration (R_A). The heterotrophic respiration (R_H) is 35-50 GtC per year. These fluxes characterise the natural and well-balanced exchange rate of about 100 GtC per year between terrestrial biota and atmosphere.

Human interference (cutting, burning, shifting of cultivation and changing of ecosystems) has not only large effects on the amount of carbon stored in the ecosystems (the reservoir), but also affects the fluxes. There has been a net release of carbon since at least 1860. Until about 1960, the annual release was greater than the release of carbon from fossil fuels. The total net release from terrestrial ecosystems since 1860 is estimated to have been 180 GtC (with a range of estimates of 135-228 GtC). The estimated net release of carbon in 1980 was 1.8-4.7 GtC, from 1958-1980 the release of C was 38-76 GtC. The ranges reflect the differences among various estimates for forest biomass, soil carbon, and agricultural clearing.

<u>Effects</u> of increasing atmospheric carbon on terrestrial biota can be expected to be caused directly by higher CO_2 concentrations and/or indirectly by changed environmental conditions due to the higher CO_2 concentrations. Among the factors affecting gross photosynthesis, light, moisture, availability of nutrients (particularly nitrogen and phosphorus) and CO_2 are the most important.

Most information relative to CO_2 effects on plants is based on data from short-term experiments under controlled conditions. Although considerable variability exists in responses of various species, an increasing growth and rate of photosynthesis is apparent and the following tentative generalisations have been made in the literature resulting mainly from experiments in glasshouses:

- The responses are greater in plants with indeterminate growth (e.g. cotton, soybean) than in plants with determinate growth (e.g. corn, maize, sorghum, sunflower).
  Plants with an indeterminate growth habit have an infinite growth potential and are the most productive, whereas the determinate plants complete their life cycle by primary growth with the production of a

complete plant.

- The response to higher levels of CO_2 is greater in C3 plants (e.g. soybean, sunflower, tomato, lettuce, cucumber, velvetleaf, wheat, sugar-beet, potato, rice, trees) than in C4 plants (e.g. corn, sorghum, millet, sugar-cane).
  In C3 plants primary photosynthetic carbon fixation occurs via the enzyme ribulose diphosphate carboxylase (RuDP) and in C4 plants via phospho-enol-pyruvate (PEP). The higher carboxylation efficiency of C4 plants has an advantage in water use efficiency and therefore in exploiting arid environments.

- The largest response is in seedlings; in older plants the response decreases or ceases. Increasing CO_2 concentration will therefore probably have the least effect on growth of plants in natural forests (dominating the biotic part of the carbon cycle), where light, water and mineral nutrition already limit the rate of photosynthesis. However, recent increases in the growth of some high-altitude trees (measured as increasing ring width) might be ascribed to increasing CO_2 concentrations, although the discussion on the causal relationship is not yet ended.

- Water use efficiency (ratio of C fixed to water consumed) increases for all species with increasing CO_2 concentrations, but particularly for C4 plants. Therefore, under conditions of significant water-stress, considerably greater proportional increases in plant productivity occur.

- Early depletion of nutrients causes a shortening of the growing season (only in C4 plants) and a significant increase of the C/N ratio in C3 plants. As N-poor plant tissue decomposes more slowly, nutrient cycling rates will then be affected in ecosystems.

Effects on ecosystems are determined by the stability of the system. In stable (climax) ecosystems (e.g. undisturbed forests) in which gross photosynthesis is equated by total respiration (NEP ≈ 0), the NEP might become positive depending on to what extent other factors are limiting (e.g. nutrients). In developing ecosystems, the NEP is permanently positive and will increase until a new (stable) equilibrium is reached. Increase of NEP will be greater where the supply of nutrients is greater, e.g. in highly productive agricultural systems. However, here the storage of carbon is only a small fraction of the annual production.

References used in this section: 5, 10, 15, 22, 24, 28, 37, 45, 67, 68, 69.

2.3.3. Carbon cycle modelling

Climate models are used to investigate the climatic response (e.g. temperature, precipitation) to changes of the atmospheric CO_2 concentration (in fact the "airborne fraction", AF). Carbon cycle models (CCM's) are the main tool for predicting the future CO_2 levels as a function of the total CO_2 emissions. To calculate these levels all processes in which CO_2 is exchanged have to be known and quantified, i.e. processes in which CO_2 is exchanged, stored and converted between the atmosphere, terrestrial biosphere and ocean.

In the last few years CCM's have become more sophisticated. There are now several dynamic, process-oriented models which represent for example accumulation and decay of dead vegetation, processing of carbon in soils and humus, and chemistry, physics and biology of the ocean. Published models have been calibrated to agree well with the change in atmospheric CO_2 concentration observed until now. However, no model has been properly validated against all trends and all data on emission rates. The most important uncertainties are:

- Future paths of energy and CO_2 emissions.
  Many of the early analyses have produced estimates of future emissions and concentrations from extrapolative techniques based on present and past emissions.
  In an attempt to address uncertainties, a second generation of studies, employing scenario analysis has arisen, which also take into account future economic and energy developments. However, there are still a number of important uncertainties in the model, e.g. rate of population growth, the availability and cost of fossil fuels, etc. (see also 3.1.).

- Diffusion rate in the ocean.
  Most models represent some features of ocean chemistry quite well, but they represent ocean physics by simple vertical diffusion coefficients, sometimes related to stratification phenomena. These one-dimensional vertical models are viewed with considerable scepticism by physical oceanographers.

- Rate of deforestation and land reclamation.
  There is disagreement about whether significant renewed growth in some areas and stimulation of plant growth by increasing atmospheric CO_2 will take place and counter losses from deforestation.

- Stimulation of growth by CO_2.
  Most carbon cycle models in estimating biotic response have depended on the so-called beta (β) factor, a measure of how much plant growth increases as a result of atmospheric CO_2 concentration.
  The numerical value of β is not known accurately at present, but is still of great importance as a parameter representing the response. However, it has been argued that the use of the β-factor should be replaced by separate analyses of the effects of changes in the area of forest and potential changes in NPP caused by both increased atmospheric CO_2 and changes in climate.

References used in this section: 9, 15, 21, 22, 45.

3. SCENARIOS AND CLIMATE MODELLING

3.1. CO_2 emissions and future energy demand

It is generally accepted that the increasing concentration of CO_2 in the atmosphere is primarily determined by the combustion of fossil fuels. In order to estimate future quantities, it is first necessary to develop pictures of the future use of fossil fuels and then to use these scenarios, in conjunction with carbon cycle models, to calculate the atmospheric CO_2 concentrations.

Understandably, many pre-1975 studies assumed that future energy growth rates would be equivalent to the historical average of 4.5% per year. However, it is now acknowledged that the "CO_2 community" should make better use of the most recent scenarios in which world energy consumption is chiefly determined by economic and socio-political forces. Most recent estimates from such sources as the US Environmental Protection Agency (EPA), the International Institute for Applied Systems Analysis (IIASA), the International Energy Agency (IEA) and the US National Academy of Sciences show that, based on calculated future CO_2 emissions, pre-industrial atmospheric concentrations could double (i.e. pass 600 ppm) some time between 2040 and 2080 (see Fig. 8), the range reflecting the uncertainties with regard to future growth and energy developments.

By combining estimates of energy demand and fuel mix, CO_2 emissions can be estimated. In Fig. 2 a number of long range CO_2 projections are presented. Estimated average annual rates of increase of CO_2 emissions until 2030 generally range from 1 to 3.5%. Estimated annual emissions range from 7 to 13 GtC in the year 2000 and, with few exceptions, from 10 and 30 GtC in 2030. The US National Research Council (NRC) forecast in 1983 that the annual increase would be about 1.6% to 2025 and about 1% thereafter compared with an average growth over the past 120 years of 3.5%. The major reasons for the lower rate are, according to the NRC, an estimated slower growth of the global economy, further conservation and a tendency to substitute non-fossil fuels for fossil fuels. (see Appendix 2 for a discussion of the NRC Report).

The energy scenarios developed by Group Planning give estimates for CO_2 emissions in the lower part of the range for a number of reasons. In the first instance, global energy intensity has been falling for many years. Figure 9 shows that in the USA the fall has been continuous since the 1920's. Since 1973, two changes have occurred: oil intensity, which had been rising, began to fall, and the decline in energy intensity accelerated.

Four factors lie behind the fall in intensity: firstly a shift in developed country economies from heavy industry to less energy-consuming light industries and services; secondly, the introduction of new technologies and processes which both directly and indirectly, consume less energy; thirdly, the development of products (cars and refrigerators, for example) which are more energy-efficient, and finally, consumers have changed their behaviour patterns to reduce energy consumption as they have become more aware of the cost of energy. While the last of these is in some sense reversible as costs decline, the first three are structural and are unlikely to be reversed.

In the future, as portrayed in the Group scenarios, the intensity continues its downward course. Indexed to 1973 = 100, the energy intensity in the OECD countries is estimated as 47 (Next Wave) or 57 (Divided World) with a probable range of 45-75. The Next Wave scenario sees a rapid take-up of technology promoting a more rapid fall in intensity. However, this is outweighed by strong economic growth and hence a relatively large increase in energy demand. In Divided World, on the other hand, energy intensity declines more slowly but economic growth is also lower so that, overall, energy demand is less than in the Next Wave.

The impact of new technology is much less in the Less Developed Countries (LDC's) where the capacity to introduce energy efficient equipment and to apply energy conservation is much less. In these countries, energy intensities are still rising although at a lower rate as technology is transferred from the developed world. In part this rise is due to the development process - the introduction of the heavy industries the countries themselves need - and partly there is the move of energy demanding industries from developed to developing countries.

The world energy demands in the year 2005 in the two scenarios are, respectively. New Wave - 209 Mbdoe (million barrels per day oil equipment) and Divided World . 193 Mbdoe. At the same time, the probable ranges are 178-220 Mbdoe and the possible ranges are 158-240 Mbdoe.

While overall energy intensity is an important variable in estimating the future production of carbon dioxide, a second factor is the <u>competition between different fuels</u> in the major markets, in particular, the relative importance of the non-fossil fuels such as hydro and nuclear. The marginal energy sources, wind, waves, hydrogen, etc., are unlikely to make sufficient contributions to have any serious effect on CO_2 levels, nor is any large move away from hydrocarbon fuels in the transport market expected and consequently changes will relate to underboiler fuels and electricity generation. Coal is expected to dominate the large industrial under-boiler market with gas and electricity becoming the major energy sources at the commercial and domestic levels. Coal and nuclear will be the chief fuels for electricity generation. Only in the long term is a shift to other energy sources likely to occur. However, as the amount of CO_2 emitted per unit of energy differs considerably (see Table 2) for the different fossil fuels, future emissions not only depend on the global energy consumption but also on the relative proportions of the fossil energy sources (see Fig. 3).

On the basis of the demand estimates from the individual fuels in each scenario the CO_2 emissions can be calculated. These are given in Table 6.

An important source of energy often ignored because of the difficulty of measurement, is the non-commercial energy (NCE): Wood, crop residues, animal and human wastes burned by the poorest members of society for heating and cooking. The population of the LDC's is approximately 3.6 billion , one third of whom depend on NCE. By 2005 the LDC population will have risen to 5.3 billion (UN estimate) and although NCE cannot rise pro rata because of the constraints on availability, nonetheless there will be an increase and this, based on estimates developed by the FAO, is included in Table 6.

In the next century, the world energy pattern can only be guessed. A key feature, however, is that because of technological change there will be a

wider variety of energy sources for exploitation than at present. However, no single new energy source will be able to meet more than 10% of the world's energy supply and coal will probably be the largest single source of hydrocarbon based energy. In addition to the main scenarios which extend only to the year 2005, some studies have been made within Group Planning on the possible use of energy in the year 2050. Based on some heroic assumptions not only of economic factors but also softer issues such as individual lifestyles and the role of government, three proto-scenarios have been developed and from these possible CO2 emissions can be calculated. These are at the very bottom of the span of estimates made by other institutions and range from 10 to 11.5 GtC per annum.

There are, of course enormous uncertainties at this distance in time surrounding not only the fuel consumption but also the split of energy sources between fossil and non fossil fuels. It may be the case that large increases in the direct use of solar energy, indirect solar such as wind or wave energy and in nuclear energy will occur as a result of unforeseen technological developments.

In the light of the possible effects of an increase in greenhouse gases, it is important to examine the likely political responses to expressions of environmental concern. Awareness of environmental matters is much stronger now than it was only a few decades ago. At present, the focus is on acid rain and nuclear energy. While opposition to nuclear is strong in the USA, Australia and some European countries, it is possible that perception of a serious environmental threat could swing opinion away from fossil fuel combustion and lead to a revival of interest in conservation, renewable sources and particularly in nuclear energy. Of course, such a movement would be stillborn if there were to be any further accidents of the Three Mile Island, Sellafield or Tsjernobyl type.

The problem is that no obvious global solution is presently conceivable which would result in a major reduction in the rate of increase of atmospheric CO2. A report issued by the US Environmental Protection Agency (EPA) in late 1983 (see Appendix 2) concluded that only draconian measures such as a global ban on coal combustion could have any significant effect. Since such actions are neither economically or politically feasible, individual countries should be urged to study ways of adapting to the inevitable rise in temperature. The NRC report referred to above, which was published at the same time, is less pessimistic in that it believes that strategies such as substantial taxation of fossil fuels might be effective.

References used in this section: 17, 21 Group Scenarios.

3.2. Projections of non-CO2 greenhouse gases

Changes in atmospheric concentrations of several infrared absorbing gases, besides CO2, result from human activities. Projections of future emissions of these trace gases are mostly at a more primitive stage than are the CO2 projections, as they are usually based on assumptions of linear increase or exponential growth relative to development in recent years.

Recently, calculations have been applied to project the concentration of each gas species. The following data have been used:
- 1980 atmospheric concentrations and recent trend data,

- nature of sources (man-made, natural, etc.),
- projected growth in natural as well as man-made sources due to expected human activities over the next 50 years, and
- atmospheric lifetimes of the species.

The resulting estimates for the year 2030 are presented in Table 4. It appears that by 2030 atmospheric CFC's may increase by a factor of 10, the chlorocarbons by a factor of 3 and the nitrogen compounds and hydrocarbons by 20% and 60%, respectively. These estimates were of course made without taking into account the effects of possible countermeasures to reduce emissions.

References used in this section: 16, 33, 35, 39, 41, 43, 46, 47, 49, 57, 61, 64.

3.3. Temperature and climatic changes

The typical approach to understanding the relationship between atmospheric CO2 and temperature has been the development of increasingly complex models of the geophysical conditions that produce global climate. Several types of mathematical models have been developed differing in comprehensiveness with regard to treatment of the climate system components. Individual models can be broadly classified as either thermodynamic (EBM's, energy balance, and RCM's, radiative-convective models, both accentuating the prediction of temperature) or hydrodynamic (predicting both the temperature and the motion fields, and their mutual interactions) models. The last category includes the now widely favoured "three dimensional" General Circulation Models (GCM's). A new model hierarchy is formed by coupling atmospheric GCM's with different ocean and sea ice models.

The standard reference value for comparing alternative models is ΔT_s (the globally averaged temperature increase due to doubled CO2). The range of surface warming simulated by the groups EBM's and RCM's for doubled CO2 is in remarkable agreement, i.e. 1.3-3.3°C. In comparing results obtained by EBM's the high and low values are usually excluded as the deviation is ascribed to the use of models that require an energy balance for the earth's surface, rather than for the entire earth-atmosphere climate system. The main proponent of the surface energy balance model is S. Idso of the US Water Conservation laboratory. On the basis of empirical observations of climatic change in Arizona and measurements of solar radiation, he concluded that ΔT_s is 0.25°C, i.e. an order of magnitude less than that predicted by the other models. This controversy within the modelling community is fundamental and will continue.

The range of surface warming simulated by the GCM's is somewhat larger than that of the purely thermodynamic models, namely 1.3-3.9°C. For this comparison calculations based on sea surface temperature/sea ice simulations were excluded from consideration, as these show a calculated present temperature lower than the presently observed temperature.

None of the above mentioned computations take the trace gas effects into account. The only, very recent, RCM simulation employing the projected increases of all greenhouse gases refers to the period up to the year 2030, the year characterised by a estimated CO2 concentration of about 450 ppm. In that study the relative importance of about 30 gases, including CO2 is taken

into consideration as well as coupled perturbations due to chemical-radiative interactions (see also section 2.2.2.). The simulation indicates that by 2030 the effects of the trace gases will amplify the CO_2 surface warming by a factor ranging from 1.5 to 3.5 (see Fig. 10).

However, the warming is not the entire story; all GCM's show an increase in the intensity of the global hydrological cycle. If the planet is warmer more moisture will evaporate from the oceans, resulting in a increase of the atmospheric water concentration. The water vapour will also act as a greenhouse gas. In addition, cloud cover might change, as well as sea ice and snow cover, all producing either an amplification or a reduction of the original effects (positive or negative "feedbacks"). Although the process of CO_2-induced warming is reasonably well understood and some of the gross features of the likely climatic change are reasonably well established qualitatively, the likely regional effects cannot be modelled with great confidence at the present time. The impact of the expected climatic change predicted by these models would be large at a doubled atmospheric CO_2 concentration, even larger than any since the end of the last ice age about 12,000 years ago (see also Appendix 8):

- precipitable water content of the atmosphere would increase by 5-15%, the precipitation rate being increased particularly at higher latitudes of both hemispheres,
- sea-ice cover of the Arctic would be reduced to a seasonal ice cover,
- snow cover would change dependent on latitude, though extent is difficult to predict,
- ice-cap mass balance change: a warming of 3°C would induce a 60-70 cm rise of the global sea level, about half of which would be due to ablation of the Greenland and Antarctic land ice, the rest to thermal expansion of the ocean; a possible subsequent disintegration of the West Antarctic Ice Sheet would result in a worldwide rise in sea level of 5-6 m,
- rising sea surface temperature would be highly regional, and
- reduced evapo-transpiration of plants would make more water available as runoff and would tend to offset the effects of any CO_2-induced reductions in precipitation or enhance the effects of precipitation increases.

Based on the modelling results, reconstruction of historical climatic conditions and studies of recent warm years and seasons, a markedly different climatic response is expected at different latitudes. The rise in the average temperature at the surface would increase from low to high latitudes in the northern hemisphere (see Fig. 1). There the projected increase would be much larger between October and May, than during the summer, thereby reducing the amplitude of seasonal temperature variations over northern lands. The models also show a large increase in the rates of precipitation and runoff at high northern latitudes (see Fig. 10). These changes could have profound effects on the distribution of the world's water resources, and large-scale effects on rain-fed and irrigated agriculture could be expected: large areas of Africa, the Middle East, India and a substantial portion of central China would cease to be water deficient areas and become favourable for agriculture. In contrast, the "food basket" areas of North America and the U.S.S.R. would become considerably drier.

References used in this section: 6, 9, 17, 21, 23, 28, 40, 43, 47, 48, 52, 53, 58, 61, 62.

3.4. Detection of the greenhouse effect

The increase in greenhouse gas concentrations from pre-industrial to the present values might have caused a significant perturbation of the radiative heating of the climate system, resulting in a warming of the global surface and lower atmosphere. The induced warming due to the increase of the $CO2$ concentration has been computed to be 0.8°C in recent RCM's and to be twice as large in a recent GCM taking into account the increase of the concentration of all (known) greenhouse gases.

Such a warming, had it indeed occurred, should have been detectable. However the search for definite evidence on whether the climate is responding to increasing concentrations of greenhouse gases, in the way that most models predict, has not yet been successful. Scientists argue that the warming is delayed through the inertia of the global system. They expect that the warming will not rise above the noise level of natural climatic variability before the end of this century. By then the ΔT_s may have risen above the natural surface temperature variation (typically ± 0.2-0.4°C for the northern hemisphere). This natural fluctuation in hemispheric or global mean temperatures, observed over the last century (see Fig. 12), is influenced by various climate forcing phenomena, e.g. solar irradiance, volcanic aerosols, and surface radiative properties, thereby making the sought-for CO2 signal unclear.

Other scientists argue that the models overestimate the temperature increase due to the increase of the greenhouse gases.In their view modellers have so far concerned themselves mainly with two climatic feedback processes, which are claimed to amplify any CO2 warming: the so-called ice-albedo feedback and the water vapour feedback. The critics argue that these two feedback processes are currently overestimated while others are completely neglected, underestimated or overestimated (for example, the carbon dioxide-ocean circulation-upwelling feedback, the CO2-ocean stability-winter down welling feedback, the CO2-Arctic sea ice-Artic biomass feedback, the CO2-rainfall distribution-tropical biomass feedback, the permafrost-methane release feedback, and the CO2-weathering of silicate minerals feedback). Overestimation of the ice-albedo feedback is particularly relevant.

It is also argued that the climate models have not been constructed with ocean surface temperature as the fundamental variable. Therefore, the inability to observe the model-calculated CO2 warming is a consequence of a lag due to thermal inertia of the ocean. In other words, the atmosphere cannot warm until the oceans do. Other studies indicate that the absorption of CO2 and heat by the oceans could possibly delay a greenhouse warming by five to twenty years.

Regardless of the continuing debate, confirmation of any view is important. If, as expected, the concentrations of the greenhouse gases gradually increase in the future, then the likelihood of achieving statistical confirmation increases. Improvements in climatic monitoring and modelling and in the historic data bases, would allow an earlier detection of any greenhouse effect with greater confidence.

References used in this section: 4, 12, 13, 17, 28, 31, 47, 58, 60, 63.

4. IMPLICATIONS

Although the greenhouse effect has been undetectable up till now, the atmospheric concentrations of the greenhouse gases are steadily increasing. Whether or not this will result in a significant global warming and if so, when it will occur, is still a matter of debate. However, without the direct need of a clear signal it is useful to give consideration to measures to counteract the likely effects. Potential effects are identified below assuming a future greenhouse effect , irrespective of uncertainties associated with timing and severity of the impact.

4.1. Potential effects of global warming induced by greenhouse gases

In this section possible effects of increasing concentrations of CO2 and the other greenhouse gases are enumerated, as well as the effects of a climate changed by global warming.

4.1.1. **Abiotic effects and biotic consequences**

I. Oceans

1. Increased water temperature	Increased growth/development rates and metabolic demands of all marine species, i.e. increased survival and growth of natural resources, through shifts of ranges and migration patterns.
2. Increased vertical stability of water masses	In turbulent (subpolar) waters increased phytoplankton production and increased fish yields. In stratified (subtropical) waters decreased phytoplankton production and decreased fish yields.
3. Decreased latitudinal and seasonal sea ice extent	Lower intensity but greater duration of primary production.
4. Temperate decrease and high latitude increase in net precipitation and runoff	Poleward species shifts due to shifts in salinity patterns.
5. Decrease in pH	Increasing tendency of dissolution of carbonate shells (e.g. shellfish), corals and sediments.
6. Rising sea level	Redistribution of nearshore and estuarine habitats, including adaptation or loss of natural resources.

II. **Agriculture**

Of the 20 food crops, that feed the world, 16 have a C3 photosynthetic pathway. The only exceptions are corn, sorghum, millet and sugarcane, which have a C4 pathway (see also chapter 2.3.2.). Of the world's 18 most noxious weeds, 14 have the C4 pathway.

1. Increasing atmospheric CO_2	Increasing productivity, providing other factors affecting plant growth (light, water, temperature, nutrients) are not adversely affected; increase in yield and harvest index, improved quality and accelerated maturity. Increase in water use efficiency and a decrease in water requirements, i.e. a greater stability of production and less crop failures.
2. Increasing CO_2 and specific crops	Greater water use efficiency with C4 plants than with C3 plants. Growth more stimulated in C3 than in C4 plants. Indeterminate plants benefit more than determinate plants. Thus, C3 plants and indeterminate plants have a higher competitive ability under optimal conditions and C4 plants will be less affected by water stress. Changes in crop/weed interactions and relationships.
3. Increased cloud cover	Increased quantum yield of net photosynthesis, i.e. beneficial effects of high CO_2 on growth when light is limited.
4. Climatic change in general	Greater resilience to environmental stress, such as high temperatures and shortage of water. Redistribution of species. Impact of changed weather is sharp in marginal climates.
5. Decrease in precipitation at 40°N and 10°S	Decreased runoff for irrigation, increase of evaporation, and decrease in yield.
6. Increase in precipitation between 10° and 20°N, north of 50°N and south of 30°S	Increase of runoff, destructive floods, and inundation of low-lying farmland.
7. Latitudinal differences in temperature rise	Increased length of growing season in temperate zone and far north latitudes. Latitudinal differences in water requirements by plants.

III. **Terrestrial ecosystems**

1. Increased atmospheric atmospheric CO_2	Increased water use efficiency. Positive response in seeding stage. Stimulation of NEP, competition induced change in total phytomass, and succesive development to a new climax vegetation. Shift of the biospheric action from CO_2 source to CO_2 sink.
2. Climatic change	Alterations of ecosystems especially in regions with strong gradients in evapo-transpiration. Major shifts in the global distributions of species.

References used in this section: 29, 32, 34, 37, 55, 65, 67.

4.1.2. Socio-economic implications

The changes in climate, being considered here, are at an unaccustomed distance in time for future planning, even beyond the lifetime of most of the present decision makers but not beyond intimate (family) association. The changes may be the greatest in recorded history. They could alter the environment in such a way that habitability would become more suitable in the one area and less suitable in the other area. Adaptation, migration and replacement could be called for. All of these actions will be costly and uncertain, but could be made acceptable. Of course, all changes will be slow and gradual and, therefore, adaptation and replacement, even migration, need not to be noticeable against the normal trends. Recognition of any impacts may be early enough for man to be able to anticipate and to adapt in time.

The adaptation of the ecosystems on earth to changes in climate, however, will be slow. It would be unrealistic to expect adaptation to occur within a few decades. Therefore, changes in ecosystem stability, disturbance of ecosystem structure and function and even local disappearance of specific ecosystems or habitat destruction could occur. This will be followed by an almost unpredictable, complex process of adaptation of the ecosystems to the changed conditions to reach a new stable situation, the so-called climax ecosystem. Quite clearly, this process of adaptation would become even more complex when it is interrupted more frequently or even continuously, such as through permanently changing climatic conditions. A new stable situation can only be expected to occur after a global settling of the change in climate. The time it then will take to reach a new stable situation depends largely on the seriousness of the disturbance of the ecosystems and, thus, on the effectiveness of the programmes to protect the earth's climate against change.

Changing temperature and precipitation are the key elements in climatic change. The main effects will be on the sea level and natural ecosystems. Socio-economic implications will be related to agriculture, fisheries, pests, water supply, etc. While the greenhouse effect is a global phenomenon, the consequences and many of the socio-economic implications will be regional and local with large temporal and spatial variations. The

following outline of possibilities is therefore incomplete and speculative, but can be a basis for further consideration and study.

1. **Rise in sea level**
   - More than 30% of the world's population live within a 50-kilometre area adjoining oceans and seas, some even below sea level. Large low-lying areas could be inundated (e.g. Bangladesh) and might have to be abandoned or protected effectively.
   - Shallow seas, lagoons, bays and estuaries characterised by extensive tidal flats could become permanently inundated. Loss of these habitats would mean a loss of extremely highly productive and diverse areas, which serve as a nursery for juveniles of all kinds of animal species and which are rich in food for fish. Effects on natural resources dependent on these systems, might therefore be dramatic (e.g. shellfish culture and fishing, seaweed harvesting, some commercially important fish).
   - There might be a shift in distribution of amenities, and as a consequence local loss of income, though at other places new sources of revenue might emerge.

2. **Rise in sea temperature**
   - Survival and growth of marine species may increase in general, though not in stratified subtropical waters. However, shifts in ranges and migration patterns could result in local losses of food sources and revenues, and could require operation in other (more distant) fishing grounds.

3. **Acidification of seawater**
   - Dissolution of $CaCO_3$ increases with a decreasing pH. Particularly in shallow coastal areas, characterised by high concentration of respiratory CO_2 and a low pH, dissolution of carbonate materials (shells, corals and sediment) could be quite rapid and result in damage of natural resources and of natural protection of shorelines, and disappearance of complete coral islands.

4. **Agriculture**
   - The impact depends on both the amplitude of climatic changes and agriculture's vulnerability to climatic variability. This vulnerability varies from region to region and will have great implication for import and export patterns of food of the countries dependent on agriculture for a larger part of their earnings some will lose some will gain. Poorer countries would run the greatest risk, the more so as their capacity to adapt would be the smallest.
   - Most farm labour is applied outdoors and is therefore essentially dependent on weather and climate. Any substantial change therein could necessitate adaptation and require new investments.
   - Model calculations show that a warmer and drier climate could decrease yields of the three great American food crops over the entire grain belt by 5 to 10%, tempering any direct advantage of CO_2 enhancement of photosynthesis. Although estimates for other areas are not available, any decrease may certainly have an impact on the world food supply and its price.
   - A warming in northern latitudes could make additional land suitable for cultivation, although the quality of such land for crops is not promising. This would result in local changes in levels of income and

working arrangements.

5. **Area of forest**
   - With a growth rate of the world population of 1.5% per year the human area increases slowly, presently mainly at the expense of grassland and agricultural land. However, decreasing yields in combination with an increasing human population may require an extension of arable land. This would certainly have implications for the tropical (and temperate) forests.
   Based on the most pessimistic predictions a disappearance of forests is expected during the first half of the 21st century, should human population growth continue indefinitely. Such a decrease in area of forest means a significant decrease of carbon fixed in the terrestrial biosphere reservoir and, consequently, an increase of atmosphere CO2
   - The natural transition line between deciduous and needle-leafed trees and the upper tree-line will shift to higher latitudes and higher elevations. Thus the total area suitable for growth of deciduous trees (mainly temperate and boreal forests) will increase.

6. **Changing air temperature**
   - Local temperature change may necessitate local adaptation of the buildings in which people live and work, technologies for heating or cooling, energy sources for heating and cooling, new food preparation technologies, new cultivation techniques, etc. All such adaptations are costly and some would drastically change the way people live and work.

7. **Water supply**
   - The prospects for water supply (sources, uses, transport, storage and conservation) are evidently of importance. Rainfall, snowfall, and evaporation are among the key elements in climate change. Level of groundwater or need of irrigation or drainage would be main determinants of whether increased rain and snow would be welcome and how costly reduced precipitation would be.
   - Local development of new sources of freshwater would be required. Water storage and transport, and inhibition of evaporation should receive continued attention.

References used in this section: 14, 15, 18, 26, 48, 50, 51.

4.1.3. **Implications for the energy industry**

Direct operational consequences can be expected from a rising sea level, impacting offshore installations, coastal facilities and operations (e.g. platforms, harbours, refineries, depots) with an uncertain magnitude. Costs of defending against a sea level rise will depend on the local situation (levels of security demanded for contingencies like extreme ocean storms, flooding, etc.) and national policies to compensate industry for the extra costs incurred.

Coal and the combined fuels of oil and gas contribute roughly equal amounts of CO2 (see Table 7). Because natural gas produces less CO2 per unit of energy, a swing from coal towards gas would reduce the CO2 emission. This argument has been used in individual choices of fuels for new power stations, but since almost 90% of the world's recoverable coal is located in

the U.S.S.R., China and the U.S., it is these countries which would have to be taking such an initiative if considered feasible.

An overall reduction in fossil fuel use would of course reduce CO_2 production and could be achieved by constraint on energy consumption, by improved thermal efficiency and by replacing fossil fuels with e.g. nuclear power. But such a course of action would imply a major shift in world energy supply and use.

Energy policy issues will be difficult to tackle because it is the world wide fossil fuel usage that affects the level of CO_2 in the atmosphere, but the mechanisms for developing world wide energy policy do not at present exist. There is little incentive for strong voluntary action by individual countries when the benefits would be shared with the rest of the world, but the costs would be borne wholly internally. Furthermore, world growth in fossil fuel use is expected to be greatest in developing countries, and they are unlikely to wish to constrain their development programmes.

The energy industry will clearly need to work out the part it should play in the development of policies and programmes to tackle the whole problem. It will not be appropriate to take the main burden, for the issues are ones that ultimately only governments can tackle, and users have an important role. But it has very strong interests at stake and much expertise to contribute, particularly on energy supply and usage. It also has its own reputation to consider, there being much potential for public anxiety and pressure group activity.

References used in this section: 2, 8, 14, 30, 50, 51, 66.

4.1.4. **Implications for Shell Companies**

For the purposes of this discussion, it is assumed that the consequence of increasing levels of carbon dioxide are as already set out, namely, an increase in air temperature, changes in weather patterns, a rise in sea level of less than 1 metre and some small increases in agricultural yields.

Possible implications include:
- Legislation affecting our products and/or processes.
- Location of Shell installations.
- Changing demand for our products:
  - liquid fuels
  - coal
  - chemicals, particularly agrochemicals
- Business opportunities:
  - alternative fuels
  - forestry
  - new varieties of plants (seeds business)

While, theoretically, it is possible to legislate for a reduction in fossil fuel use, it must be the case that any global reduction is most unlikely. However, in a paper produced as background information for the latest set of energy scenarios, Group Planning felt there was a possibility that an increasing awareness of the greenhouse effect might change peoples' attitudes towards non-fossil energy sources, especially nuclear.

Fossil fuels which are marketed and used by the Group account for the production of 4% of the CO_2 emitted worldwide from combustion. Of these emissions, 80% comes from Group oil, 12% from Group gas and 8% from Group coal (see Tables 7 and 8).

It is thermodynamically unfavourable and technically very difficult to remove carbon dioxide from the air other than by planting trees. If an international effort were mobilised to do this, and the poor response to the World Bank's call for such effort currently makes it appear unlikely, then there would be some call on companies, including Shell, with experience in tropical forestry.

Of the other greenhouse gases, many are chemicals in commercial use which could in principle be replaced or banned; it is difficult, on the other hand to see what could be done about others such as methane.

There seems little need to consider changes in the location of Shell installations because of the slowness of changes in sea level in the chosen time-frame. Climatic change could alter the relative wealth of certain LDC's and lead us to examine the possibilities of expanding or contracting our business accordingly.

These same changes, by altering the patterns of agriculture could alter up or down the demand for our agricultural products both chemicals and seeds, though it is difficult to forecast the effect of the biotechnological revolution on this area - it might swamp any effect of increasing carbon dioxide.

5. SCOPE FOR FURTHER ACTION

The existing large uncertainties surrounding the possible consequences of the increasing atmospheric CO2 concentration divide those who at least see substance in the theory, in the following three basic categories:
1. Those who believe there is no need for short-term action and insufficient knowledge about how to tackle the problem, so that nothing need be done for the moment other than to narrow the existing uncertainties,
2. Those who believe that the threat is real, and seek to eliminate the problem, and
3. Those who believe that the threat is real and unavoidable, so that "learning to live with climatic change" is the only solution.

Some people may, of course, lie between these categories, e.g. those who believe the threat is not considerable and who seek both to reduce its intensity and to adapt to it.

From these groups came a number of actions and strategies which are believed most appropriate. Current (1986) official, government attitude mainly fit the first approach, though there is a tendency to carry out analyses that would eventually lead to discussion of remedial measures (see also Appendix 3).

First group
- Basic research and monitoring:
  - ° monitoring of causal factors:
    emission of greenhouse gases
    atmospheric concentration of these gases
    solar variations
    volcanic aerosol
    changes in area of forest
  - ° climatic effects:
    temperature
    radiation fluxes
    precipitable water content
    cloud cover
    sea level
    sea temperature
    snow and sea-ice cover (remote sensing)
- Applied research and development:
  - ° agriculture:
    responses of ecosystems
    crop yields
    physiology and growth
  - ° water resources

Second group
- Analysis of economic and social costs associated with climate change
- Reduction of releases of greenhouse gases other than CO2
- Management of biota:
  - ° freezing rate of deforestation
  - ° freezing land reclamation
  - ° freezing rangeland burning
  - ° promotion of re-/afforestation

  ° fertilisation of the ocean surface with phosphorus and nitrogen, thereby increasing the biotic fixation of CO2 (generating other adverse effects)
- Removal of CO2:
  ° deep-sea disposal of CO2 produced at centralised location (consequently generating secondary effects)
  ° re-/afforestation
- Energy research and policy:
  ° development of renewable energy sources:
    solar energy
    biomass conversion
    geothermal energy
    hydroelectric energy
    utilisation of energy contained in waste
    wind energy
  ° rational use of energy:
    energy saving
    new energy carriers
  ° analysis of energy systems (energy-economy models):
    open ended versus closed ended systems (open ended systems are those which through evolution in the use of end products allow satisfaction of energy needs without increasing use of fixed carbon sources)
- Energy management:
  ° reduction of fossil fuel usage
  ° usage of low-carbon fuels
  ° usage of alternative energy sources

Third group
- Adaptation to climatic changes through:
  ° changes in environmental control
  ° migration
- Adaptation to sea level rise through:
  ° migration
  ° construction of (higher) dikes
- Adaptation to effects on agriculture through:
  ° migration
  ° change of crops
  ° modification of varieties
  ° alteration of husbandry

If the environmental problem develops as some predict, then the impact would be sufficiently large as to require a policy response. Re-direction of research emphasis towards analysis of energy and policy options will then require particular attention.

It should be noted that, when CO2 becomes the focus of concerted international action, the developing nations will be particularly affected.

References used in this section: 8, 10, 14, 19, 30, 38, 51, 66,69.

6. REFERENCES

1. Ausubel, J.H.; Nordhaus, W.D.
A review of estimates of future carbon dioxide emissions.
In: National Research Council, Changing Climate, Report of the Carbon dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 153-185, 1983.

2. Baxendell, P.
The changing energy balance in Asia Pacific.
Address to the PetroPacific '84 Congress, Melbourne, Australia, 8 pp., 1984.

3. Brewer, P.G.
Carbon dioxide and the oceans.
In: National Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 188-215, 1982.

4. Broecker, W.S.; Peteet, D.M.; Rind, D.
Does the ocean-atmosphere system have more than one stable made of operation?
Nature 315:21-25, 1985.

5. Brown, S.; Lugo, A.E.
Biomass of tropical forests: a new estimate based on forest volumes.
Science 123:1290-1293, 1984.

6. Bryan, K.
The role of the ocean in the transient climate response to increasing atmospheric CO2.
In: Proc. Joint Oceanographic Assembly 1982, Gen. Symp. Halifax, pp 43-46, 1983.

7. Byrne, R.H.; Acker, J.G.; Betzer, P.R.; Feely, R.A.; Cates, M.H.
Water column dissolution of aragonite in the Pacific Ocean.
Nature 312:321-326, 1984.

8. Compton, W.D.
Alternate fuels - a technology that is ready.
UP Front/Agricultural Engineering 66:12-13, 1985.

9. Crane, A.J.
Possible effects of rising CO2 on climate.
Plant Cell Environ. 8:371-379, 1985.

10. Dahlman, R.C.; Strain, B.R.; Rogers, H.H.
Research on the response of vegetation to elevated atmospheric carbon dioxide.
J. Environ. Qual. 14:1-8, 1985.

11. Duplessy, J.-C.; Shackleton, N.J.
Response of global deep-water circulation to earth's climatic change 135,000-107,000 years ago.
Nature 316:500-507, 1985.

12. Ellsaesser, H.W.
The climatic effect of CO2: a different view.
Atmospheric Environment 18:431-434, 1984.

13. Fritts, H.C.; Lough, J.M.
An estimate of average annual temperature variations for North America, 1602 to 1961.
Climatic Change 7:203-224, 1985.

14. Golanty, E.
The global experiment. Carbon dioxide and ocean temperature.
Oceans 17:66-69, 1984.

15. Goudriaan, J.; Ketner, P.
A simulation study for the global carbon cycle, including man's impact on the biosphere.
Climatic Change 6:167-192, 1984.

16. Hameed, S.; Cess, R.D. Hogan, J.S.
Response of the global climate to changes in atmospheric chemical composition due to fossil fuel burning.
J. Geophys. Res. 85:7537-7545, 1980.

17. Hansen, J; Johnson, D.; Lacis, A.; Lebedeff, S.; Lee. P.; Rind, D.; Russel, G.
Climate impact of increasing atmospheric carbon dioxide.
Science 213:957-966, 1981.

18. Hartwig, S.; Heudorfer, W.; Schnatz, G.
Possible climatic change by anthropogenic CO2 emission.
J. Chem. E. Symposium Series, No. 78, T4/15-T4/30, 1982.

19. Heintzenberg, J.; Hansson, H.-C.; Ogren, J.A.; Odh, S.-A.
Concept and realisation of an air pollution monitoring station in the European Arctic.
Ambio 14:152-157, 1985.

20. Hileman, B.
The greenhouse effect.
Environ. Sci. Technol. 16:90A-93A, 1982.

21. Hileman, B.
Recent reports on the greenhouse effect - what are some differences between the EPA and NRC studies?
Environ. Sci. Technol. 18:45A-46A, 1984.

22. Hobbie, J.; Dungan, J.; Houghton, R.A.; Peterson, B.
Role of biota in global CO2 balance: the controversy.
BioScience 34: 492-498, 1984.

23. Hoffert, M.I.; Callegari, A.J.; Hsiek, C.T.
The role of deep sea heat storage in the secular response to climatic forcing.
J. Geophys. Res. 85:6667-6679, 1980.

24. Houghton, R.A.; Hobbie, J.E.; Melillo, J.M.; Moore, B.; Peterson, B.J.; Shaver, G.R.; Woodwell, G.M.
Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO2 to the atmosphere.
Ecol. Monogr. 53:235-262, 1983.

25. Hugill, J.A.
The carbon dioxide greenhouse effect.
KSLA, report AMGR.80.105, 9 pp, 1980.

26. Ichimura, S.
The impacts of climatic change on human society.
In: Carbon dioxide Effects Research and Assessment Program. Workshop on Environmental and Societal Consequences of a Possible CO2 Induced Climate Change. U.S.-DOE, Conf-7904143, pp 442-462, 1980.

27. Idso, S.B.
Temperature limitation by evaporation in hot climates and the greenhouse effects of water vapour and carbon dioxide.
Agric. Meterol. 27:105-109, 1982.

28. Idso, S.B.
The search for global CO2 ect. "Greenhouse Effects".
Environ. Conservation 12:29-35, 1985.

29. Idso, S.B.; Brazel, A.J.
Rising atmospheric carbon dioxide concentrations may increase streamflow.
Nature 312:51-53, 1984.

30. Jaske, R.T.
Carbon dioxide - the premier environmental challenge of our time.
Environ. Progress 2:145-148, 1983.

31. Kellogg, W.W.
Feedback mechanisms in the climate system affecting future levels of carbon dioxide.
J. Geophys. Res. 88:1263-1269, 1983.

32. Kendall, A.C.; Turner, J.C.; Thomas, S.M.
Effects of CO2 enrichment at different irradiances on growth and yield of wheat.
J. Exp. Bot. 36:252-260, 1985.

33. Kerr, R.A.
Doubling of atmospheric methane supported.
Science 226:954-955, 1984.

34. King, D.A.
Estimating the direct effect of CO2 on soybean yield.
J. Environ. Mngt 20:51-62, 1985.

35. Kondratyev, K. Ya.; Bunakova, A.M.
Factors of the greenhouse effect of the atmosphere and their influence on climate.
In: Williams, J. (ed.), Carbon Dioxide, Climate and Society. Pergamon Press, Oxford, pp 201-207, 1978.

36. Kratz, G.
Modelling the global carbon cycle.
In: Hutzinger, O. (ed.), The Handbook of Environmental Chemistry, Vol. 1, Part D. Springer Verlag, Berlin, pp 29-81, 1985.

37. Lallarche, V.C.; Graybill, D.A.; Fritts, H.C.; Rose, M.R.
Increasing atmospheric carbon dioxide: tree ring evidence for growth enhancement in natural vegetation.
Science 225:1019-1021, 1984.

38. Laurmann, J.A.
The global greenhouse warming problem: setting the priorities.
Climatic Change 7:261-265, 1985.

39. Levine, J.S.; Rinsland, C.P.; Tennille, G.M.
The photochemistry of methane and carbon monoxide in the troposphere in 1950 and 1985.
Nature 318:254-257, 1985.

40. Manabe, S.; Stouffer, R.J.
Sensitivity of a global climate model to an increase of CO2 concentration in the atmosphere.
J. Geophys. Res. 85:5529-5554, 1980.

41. Maugh, T.H.
What is the risk from chlorofluorocarbons?
Science 223: 1051-1052, 1984.

42. Mook, W.G.; Engelsman, F.M.R.
Het atmosferische CO2 gehalte en de rol van de oceanen.
Chemisch Magazine, Dec. 1983:669-671, 1983.

43. Nicoli, M.P. Visconti, G.
Impact of coupled perturbations of atmospheric trace gases on earth's climate and ozone.
Pageoph. 120:626-641, 1982.

44. Papaud, A.; Poisson, A.
Le cycle du carbone et sa perturbation par les activités humaines: un apercu du problème.
Oceanologica Acta 8:133-145, 1985.

45. Pearman, G.I.; Hyson, P.
Activities of the global biosphere as reflected in atmospheric CO2 records.
J. Geophys. Res. 85:4468-4474, 1980.

46. Ramanathan, V.
Greenhouse effect due to chlorofluorocarbons: climatic implications.
Science, 190,50-52, 1975.

47. Ramanathan, V.; Cicerone, R.J.; Singh, H.B.; Kiehl, J.T.
Trace gas trends and their potential role in climate change.
J. Geophys. Res. 90:5547-5566, 1985.

48. Revelle, R.
Carbon dioxide and world climate
Sci. Amer. 247:33-41, 1982.

49. Rinsland, C.P.; Levine, J.S.; Miles, T.
Concentration of methane in the troposphere deduced from 1951 infrared solar spectra.
Nature 318:245-249, 1985.

50. Schelling, T.C.
Climatic change: implications for welfare and policy.
In: Natural Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 449-482, 1983.

51. Schelling, T.C.
Climatic change: implications for welfare and policy.
Ambio 13:200-201, 1984.

52. Ichlesinger, M.E.
Climate model simulations of CO2-induced climatic change.
Adv. Geophysics 26:141-235, 1984.

53. Semtner, A.J.
On modelling the seasonal thermodynamic cycle of sea ice in studies of climatic change.
Climatic Change 6:27-37, 1984.

54. Shackleton, N.J.; Hall, M.A.; Line, J.; Shuxi, C.
Carbon isotope data in core V19-30 confirm reduced carbon dioxide concentration in the ice age atmosphere.
Nature 306:319-322, 1983.

55. Shugart, H.H.; Emanuel, W.R.
Carbon dioxide increase: the implications at the ecosystem level.
Plant Cell Environ. 8:381-386, 1985.

56. Smith, S.V.
Physical, chemical and biological characteristics of CO2 gas flux across the air-water interface.
Plant, Cell Environ. 8:387-398, 1985.

57. Stauffler, B.; Fischer, G.; Neftel, A.; Oeschger, H.
Increase of atmospheric methane recorded in Antarctic ice core.
Science 229:1386-1388, 1985.

58. Stewart, T.R.; Glantz, M.H.
Expert judgment and climate forecasting: a methodological critique of "climate change to the year 2000".
Climatic Change 7:159-183, 1985.

59. Tyndall, J.
On the absorption and radiation of heat by gases and vapours, and on the physical connection of radiation, absorption, and conduction.
Philosoph. Mag. Ser. 4:169-194 and 273-285, 1861.

60. Walker, J.C.G.; Hays, P.B.; Kasting, J.F.
A negative feedback mechanism for the long-term stabilisation of earth's surface temperature.
J. Geophys. Res. 86:9776-9782, 1981.

61. Wang. W.C.; Yung, Y.L.; Lacis, A.A.; Mo, T.; Hansen, J.E.
Greenhouse effects due to man-made perturbations of trace gases.
Science 194:685-690, 1976.

62. Washington, W.M.; Meehl, G.A.
Seasonal cycle experiment on the climate sensitivity due to a doubling of CO2 with an atmospheric general circulation model coupled to a simple mixed-layer ocean model.
J. Geophys. Res. 89:9475-9503, 1984.

63. Weller, G.; Baker, D.J.; Gates, W.L.; MacCracken, M.C.; Manabe, S.; Vonder Haas, T.H.
Detection and monitoring of CO2 induced climate changes.
In: National Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 292-382, 1983.

64. Wigley, T.M.L.
Carbon dioxide, trace gases and global warming.
Climate Monitor 13:133-146, 1984.

65. Wigley, T.M.L.; Jones, P.D.
Influences of precipitation changes and direct CO2 effects on streamflow.
Nature 314:149-152, 1985.

66. Williams, R.H.
Potential roles for bioenergy in an energy-efficient world.
Ambio 14:201-209, 1985.

67. Wittwer, A.J.
Carbon dioxide levels in the biosphere: effects on plant productivity.
CRC Crit. Rev. Pl. Sci. 2:171-198, 1985.

68. Woodwell, G.M.
Biotic effects on the concentration of atmospheric carbon dioxide: a review and projection.
In: Natural Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp. 216-241, 1983.

69. Woodwell, G.M.; Hobbie, J.E.; Houghton, R.A.; Melillo, J.M.; Moore, B.; Peterson, B.J.; Shaver, G.R.
Global deforestation: contribution to atmospheric carbon dioxide.
Science 222: 1081-1086, 1983.

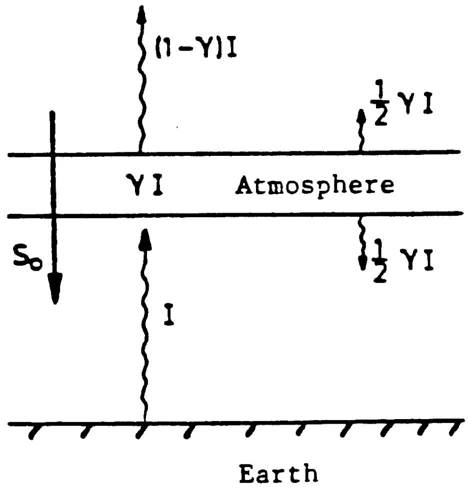


Figure 1

The greenhouse effect: S_o is the solar radiation, I the long-wavelength (infrared) radiation of the earth's surface and Y is the fraction absorbed by the greenhouse gases in the atmosphere (source: Mureau, R. Kooldioxyde (CO_2) en klimaat. In: Hermans, L.J.F.; Hoff, A.J. (eds), Energie een blik in de toekomst. Het Spectrum, Utrecht, The Netherlands, pp 68-86, 1982).

The sun's energy passes through the atmosphere, warms the earth's surface, and is then reradiated into space at longer, infrared wavelengths.
The balance of incoming and outgoing radiation determines the planet's temperature. Some atmospheric gases absorb some of the outgoing infrared (e.g. CO_2 in a band of 14-16 μm), trapping heat in a "greenhouse effect".

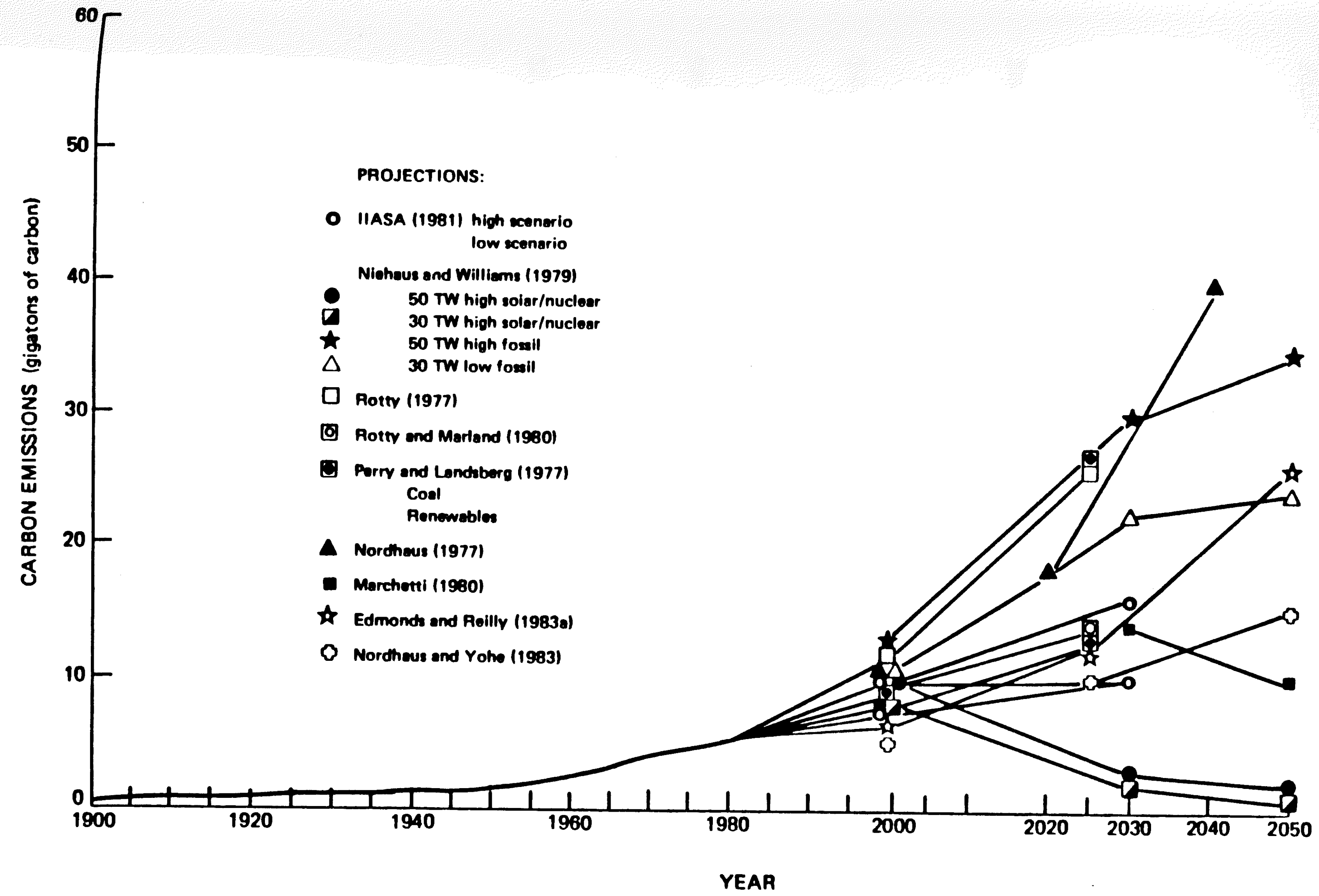


Figure 2

CO_2 emissions derived from long-range projections and historic production from fossil fuels. Data until 1980 are actual measurements; after 1980 model-calculated projections (source: Carbon Dioxide Assessment Committee, Changing Climate. National Academy Press, Washington, DC, 1983).

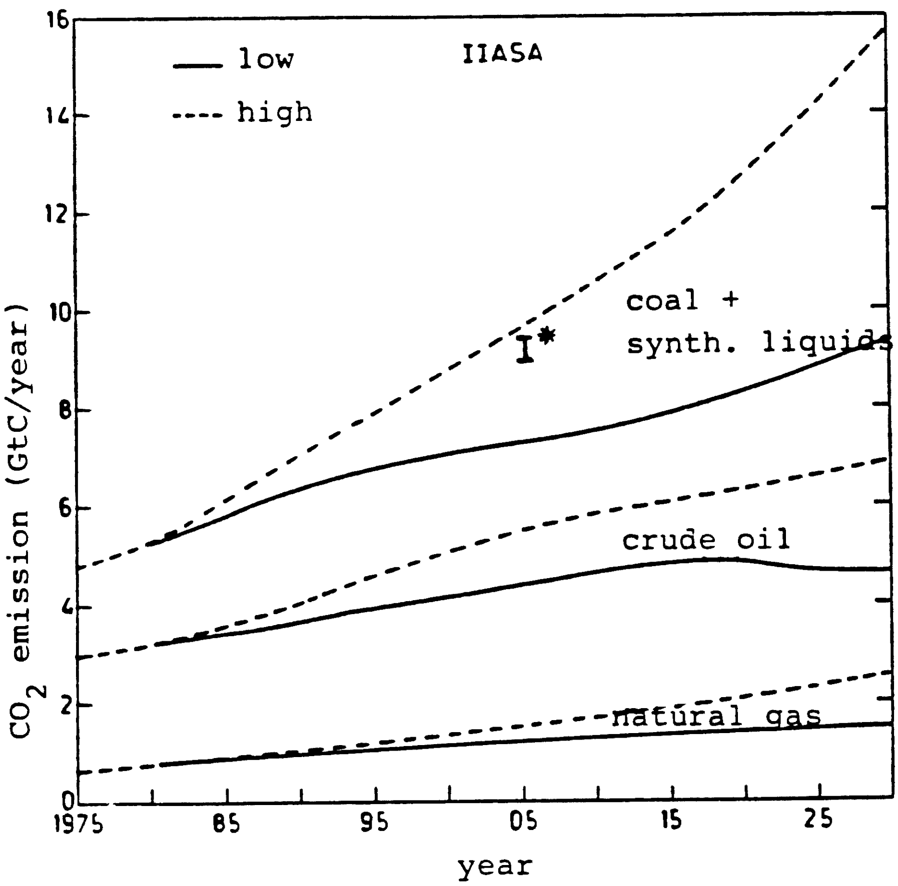


Figure 3

Projected CO_2 emissions generated with the IIASA Energy Systems Programme. For the individual fuels the emissions are cumulatively presented for the lower- and higher-demand cases (source: Deeladvies inzake CO_2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983).

* Shell scenario figures for total emissions.

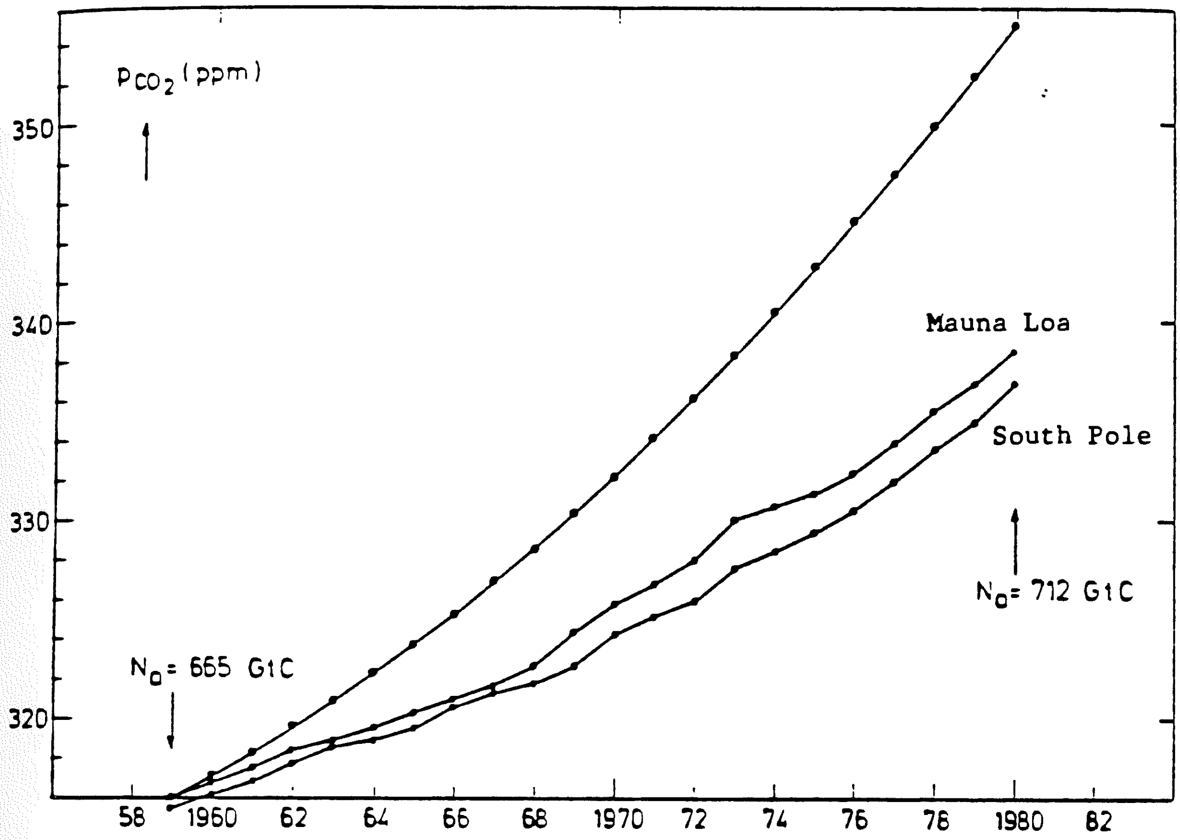


Figure 4

The hypothetical atmospheric CO_2 concentrations based on man-made CO_2 emissions with AF=100% (airborne fraction) and the observed concentrations at Mauna Loa and the South Pole with AF=56%; N_a is the amount of carbon present in the atmosphere (source: Deeladvies inzake CO_2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983).

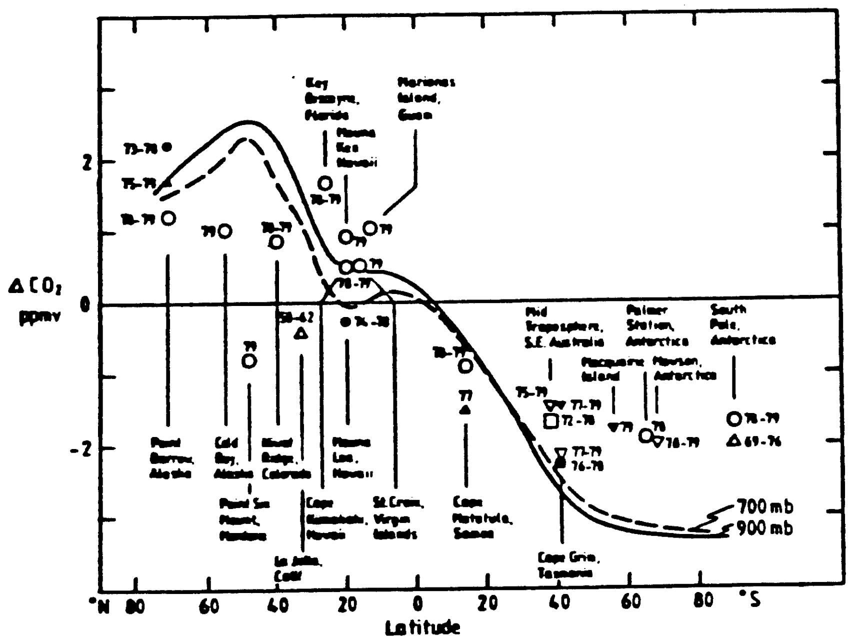


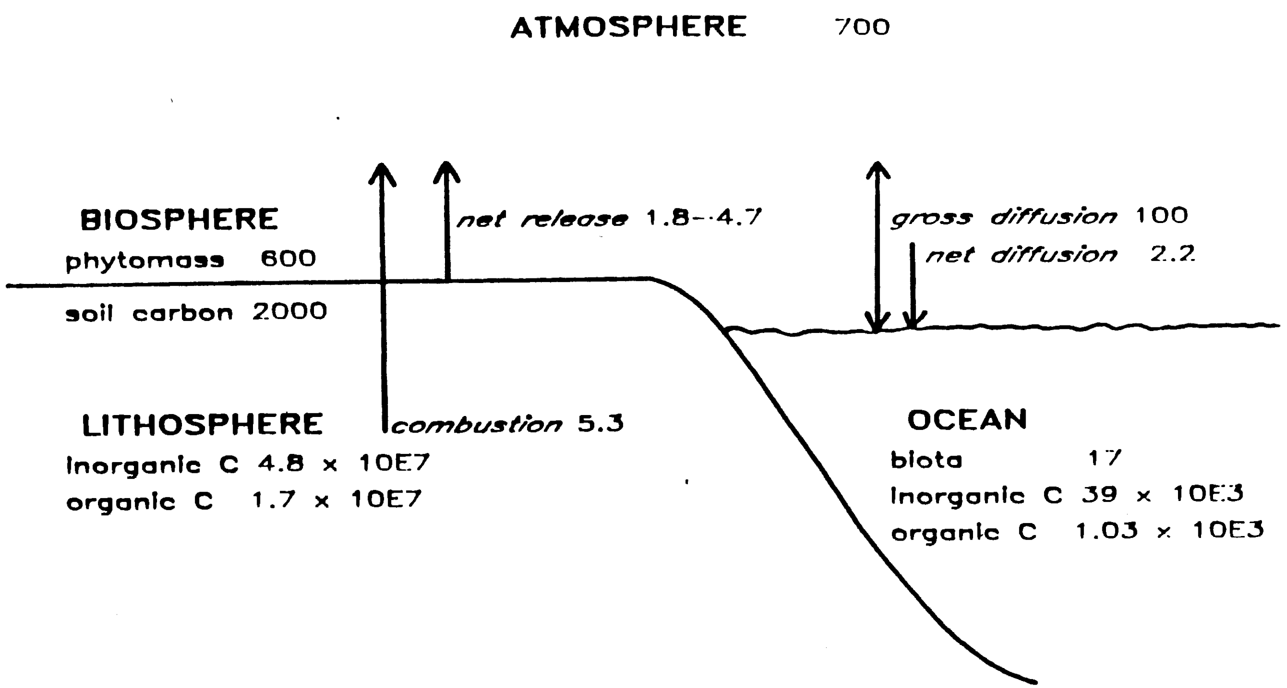
Figure 5

Difference between the annual mean CO_2 concentration in the air at ground-level observed at different places in the world and at Mauna Loa, Hawaii, plotted as a function of latitude. The numbers adjacent to the data points indicate the observation time (source: Papaud, A.; Poisson, A., Le cycle du carbon et sa perturbation par les activités humaines: un apercu du problème. Oceanologica Acta 8:133-145, 1983).

N.B. The two lines represent the model simulations at the altitudes corresponding with 700 and 900 mbar.

Figure 6

The global carbon cycle.
Major carbon reservoirs (in GtC), and natural and (quantified) anthropogenic fluxes (in GtC per year).
1 GtC = 1 gigaton of carbon = 10^{15} g C.



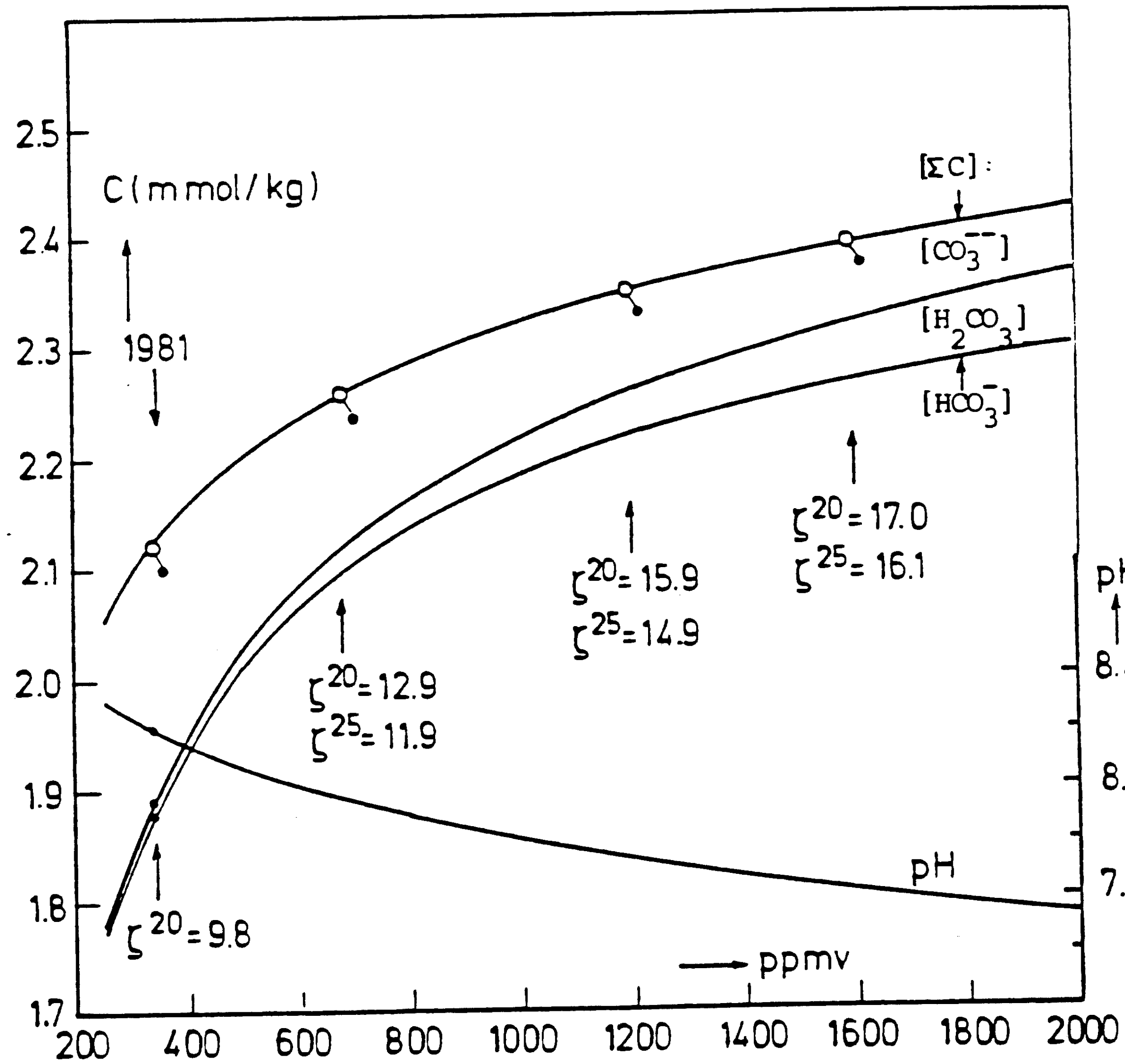


Figure 7

Variation of the buffer factor of seawater with changing total CO_2. Concentrations (at 20°C) of total dissolved inorganic carbon (DIC = ΣC) and of HCO_3^- in seawater (in mM/kg) are given in relation to the partial pressure of carbon dioxide gas (pCO_2 in ppmv). The concentrations of dissolved CO_2 (H_2CO_3) and of CO_3^{2-} are given as difference between the curves. For a few CO_2 concentrations (e.g. the 1981 value of 340 ppmv and its doubling) the buffer factors ζ^{20} (at 20°C) and ζ^{25} (at 25°C) are given. Increasing CO_2 levels raise the buffer factor, diminish the oceans tendency to absorb CO_2 (i.e. proportionally less increase in oceanic carbon) and decrease pH (source: Deeladvies inzake CO_2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983).

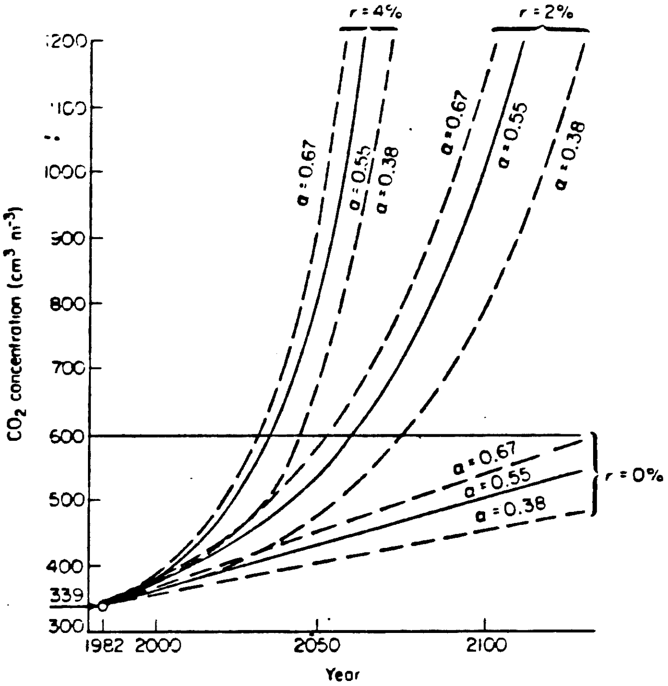


Figure 8

Increase in atmospheric CO_2 concentration over the next 150 years assuming growth rate in emissions of 4, 2 and 0% per year (r) for airborne fractions (α) of 0.38, 0.55 and 0.67 (source: Liss, P.S.; Crane, A.J., Man-made Carbon Dioxide and Climatic Change: a Review of Scientific Problems. Geobooks, Norwich, 1983).

The growth rate of CO_2 emissions from 1973 to the early 1980s fell to below 2% per year and there is a consensus now that the most likely time for a doubling of the CO_2 concentration (i.e. passing 600 ppm) lies in the third quarter of the next century.

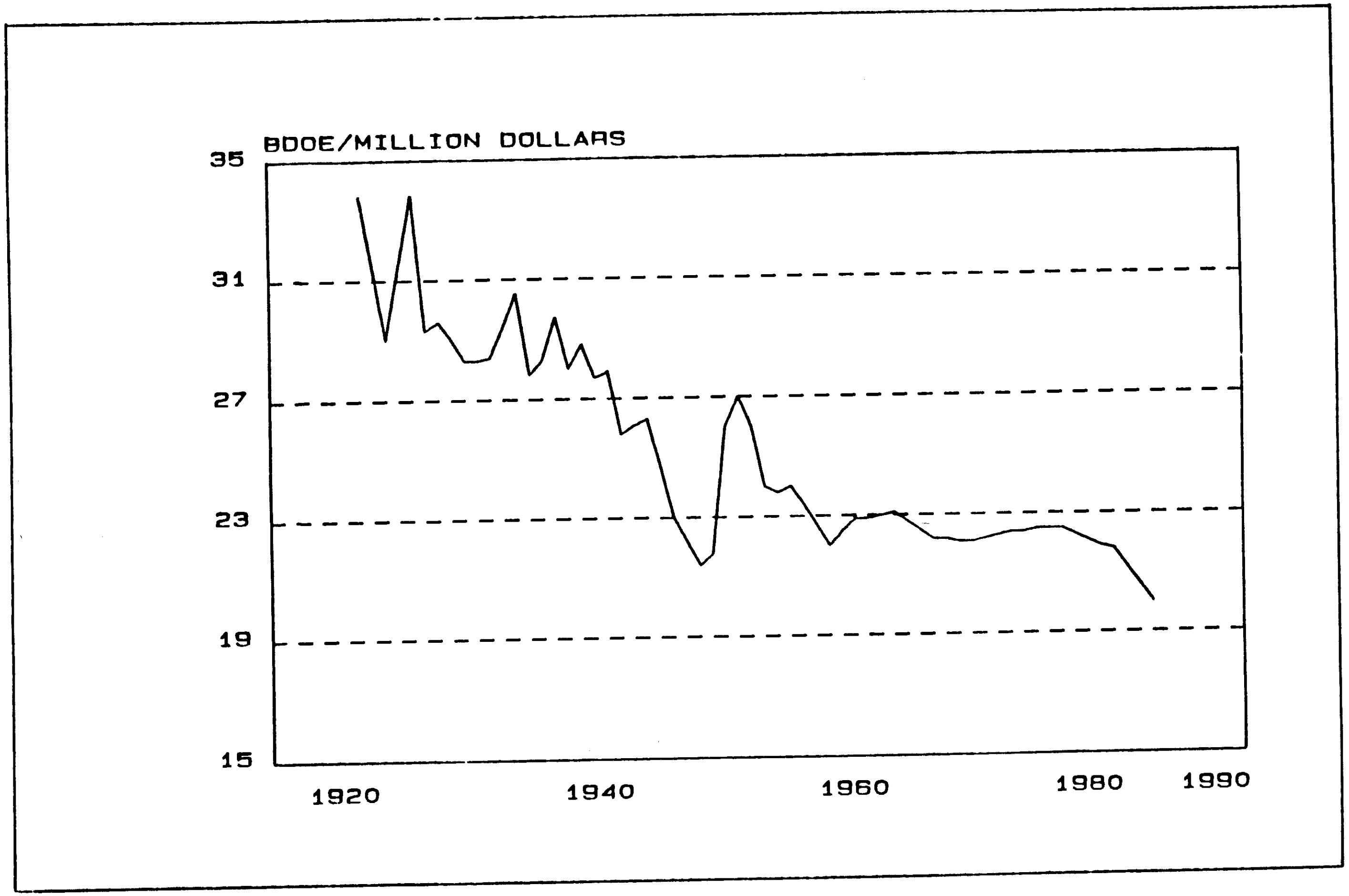


Figure 9

Falling energy intensity in the USA (source: Group Planning Scenarios).

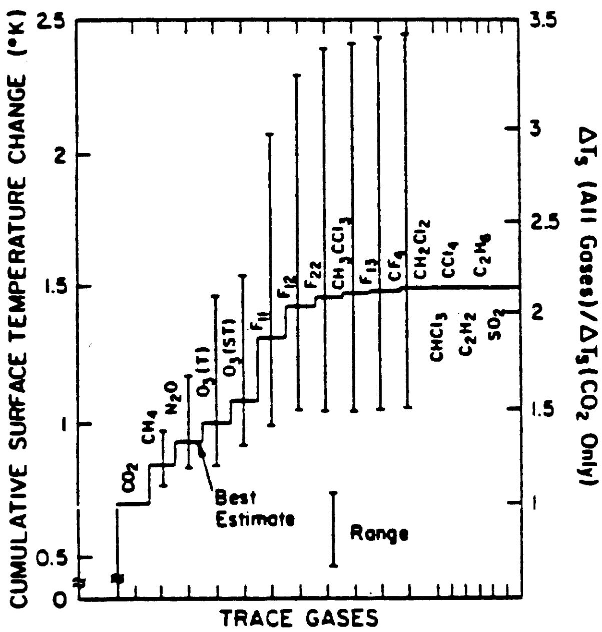


Figure 10

Modelled cumulative surface warming due to increase in CO_2 and other gases over the period 1980 to 2030 (source: Ramanathan, V. et al., Trace gas trends and their potential role in climate change. J. Geophys. Res. 90:5547-5566, 1985).

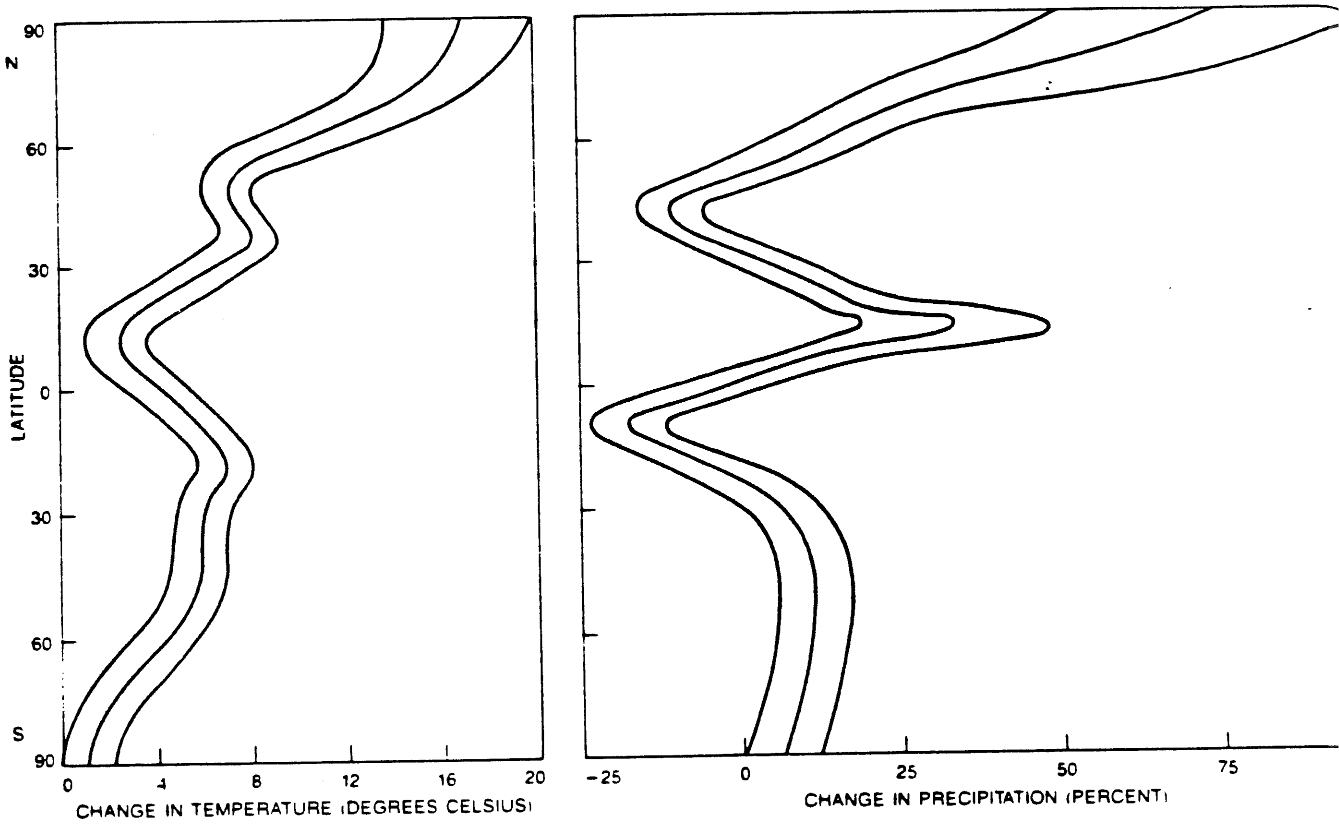


Figure 11

Modelled climatic effects of a doubling of the present atmospheric CO_2 concentration. The graphs show the projected variation by latitude in temperature and precipitation. The three curves in each group reflect the range of possibilities (source: Revelle, R., Carbon dioxide and world climate. Sci. Amer. 247:33-41, 1982).

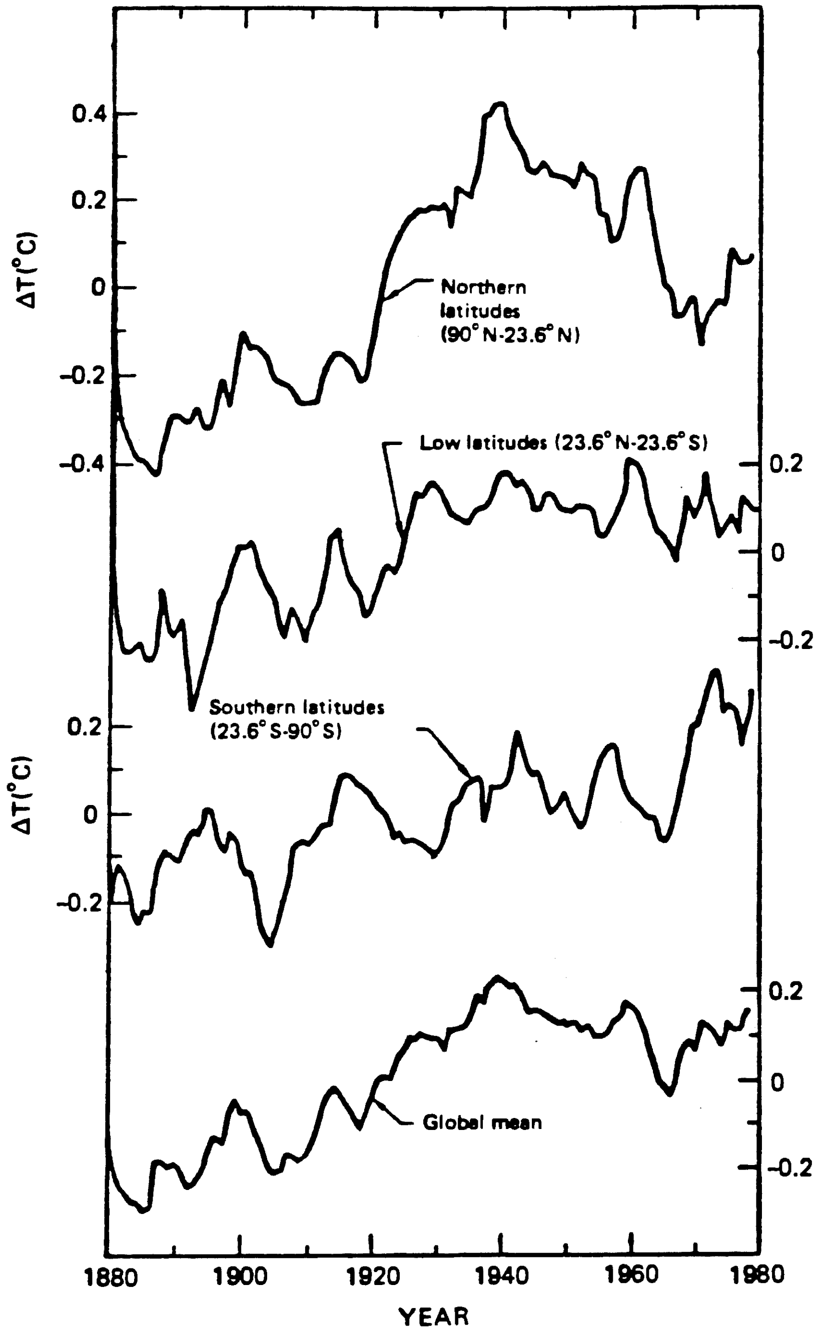


Figure 12

Reconstruction of surface-air-temperature anomalies for various latitude bands (source: Hansen, J. et al., Climate impact of increasing atmospheric carbon dioxide. Science 213:957-966, 1981).

Table 1. CO2 emissions per year by fuel type (10^6 tonnes C/year) (source: Jaske, R.T., Carbon dioxide - the premier environmental challenge of our time. Environ. Progress 2:145-148, 1983)

	1950	1975	1980	% increase 1950-75	% increase 1975-80
all fossil fuels	1600	4400	5000	4.46	1.86
coal and coal products	1100	1600	1950	1.72	2.57
oil and refined products	400	2200	2300	2.11	1.11
gas and gas by-products	100	600	750	8.06	3.23

Table 2. Carbon produced (as CO2) from selected energy sources (source: Jaske, R.T., Carbon dioxide - the premier environmental challenge of our time. Environ. Progress 2:145-148, 1983)

Fuel source or type	CO2 per fuel energy content (kg/MJ)
coal in direct combustion	23.9
liquid fuel from crude oil	19.7
natural gas	14.1
synthetic liquids from coal	37 - 42
synthetic liquids from shale	43 - 66

Table 3. CO2 emissions per region (in GtC) and per capita (in tC) in 1975 (GtC = 1 gigaton of carbon = 10^9 ton of C = 10^{15} g carbon = 44/12 GtCO2)
(source: Deeladvies inzake CO2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983)

region	CO2 emission	population (millions)	CO2 emissions per capita
North America	1.426	237	6.017
USSR + E. Europe	1.218	363	3.355
W. Europe, Japan S. Africa, Australia Israel, New Zealand	1.391	560	2.484
L. and M. America	0.160	319	0.502
M. Africa + S.E. Asia	0.163	1422	0.115
Middle East + N. Africa	0.058	133	0.436
China + Central Asia	0.296	912	0.325
World	4.712	3946	1.194

Table 4. Estimates of the abundance of trace chemicals in the global atmosphere of 1980 and 2030 (source: ref. 47)

Chemical Group	Chemical Formula	Dominant Source*	Dominant Sink*	Estimated Average Residence Time (τ_r), years	Year 1980 Global Average Mixing Ratio, ppb†	Year 2030 Probable Global Average Concentration, ppb: Best Estimate	Year 2030 Probable Global Average Concentration, ppb: Possible Range	Remarks (also see text for details)
Carbon dioxide	CO_2	N,A	O	2	339×10^3	450×10^3		Based on a 2.4% increase over the next 50 years
Nitrogen compounds	N_2O	N,A	S(UV)	120	300	375	350-450	Combustion and fertilizer sources
	NH_3	N,A	T	0.01	<1	<1		Concentration variable and poorly characterized
	$(NO + NO_2)$	N,A	T(OH)	0.001	0.05	0.05	0.05-0.1	Concentration variable and poorly characterized
Sulfur compounds	CSO	N,A	T(O,OH)?	1(?)	0.52	0.52		Sources and sinks largely unknown
	CS_2	N,A	T	1(?)	<0.005	<0.005		Sources uncharacterized
	SO_2	A(?)	T(OH)	0.001	0.1	0.1	0.1-0.2	Given the short lifetime the global presence of SO_2 is unexplained
	H_2S	N	T(OH)	0.001	<0.05	<0.05		
Fully fluorinated species	CF_4 (F14)	A	I	>500	0.07	0.24	0.2-0.31	Aluminum industry a major source
	C_2F_6 (F116)	A	I	>500	0.004	0.02	0.01-0.04	Aluminum industry a major source
	SF_6	A	I	>500	0.001	0.003	0.002-0.05	
Chlorofluorocarbons	$CClF_3$ (F13)	A	S(UV),I	400	0.007	0.06	0.04-0.1	All chlorofluorocarbons are of exclusive man-made origin. A number
	CCl_2F_2 (F12)		S(UV)	110	0.28	1.8	0.9-3.5	of regulatory actions are pending. The nature of regulations and
	$CHClF_2$ (F22)	A	T(OH)	20	0.06	0.9	0.4-1.9	their effectiveness would greatly affect the growth of these
	CCl_3F (F11)	A	S(UV)	65	0.18	1.1	0.5-2.0	chemicals over the next 50 years.
	CF_2CF_2Cl (F115)	A	S(UV)	380	0.005	0.04	0.02-0.1	
	$CClF_2CClF_2$ (F114)	A	S(UV)	180	0.015	0.14	0.06-0.3	
	CCl_2FCClF_2 (F113)	A	S(UV)	90	0.025	0.17	0.08-0.3	
Chlorocarbons	CH_3Cl	N(O)	T(OH)	1.5	0.6	0.6	0.6-0.7	Dominant natural chlorine carrier of oceanic origin
	CH_2Cl_2	A	T(OH)	0.6	0.03	0.2	0.1-0.3	A popular reactive but nontoxic solvent
	$CHCl_3$	A	T(OH)	0.7	0.01	0.03	0.02-0.1	Used for manufacture of F22; many secondary sources also exist
	CCl_4	A	S(UV)	25-50	0.13	0.3	0.2-0.4	Used in manufacture of fluorocarbons; many other applications as well
	CH_2ClCH_2Cl	A	T(OH)	0.4	0.03	0.1	0.06-0.3	A major chemical intermediate (global production ≈ 10 tg/yr); possibly toxic
	CH_3CCl_3	A	T(OH)	8.0	0.14	1.5	0.7-3.7	Nontoxic, largely uncontrolled degreasing solvent
	C_2HCl_3	A	T(OH)	0.02	0.005	0.01	0.005-0.02	Possibly toxic, declining markets because of substitution to CH_3CCl_3
	C_2Cl_4	A	T(OH)	0.5	0.03	0.07	0.03-0.2	Possibly toxic, moderate growth due to substitution to CH_3CCl_3
Brominated and iodated species	CH_3Br	N	T(OH)	1.7	0.01	0.01	0.01-0.02	Major natural bromine carrier
	$CBrF_3$ (F13B1)	A	S(UV)	110	0.001	0.005	0.003-0.01	Fire extinguisher
	CH_2BrCH_2Br	A	T(OH)	0.4	0.002	0.002	0.001-0.01	Major gasoline additive for lead scavenging; also a fumigant
	CH_3I	N	T(UV)	0.02	0.002	0.002		Exclusively of oceanic origin
Hydrocarbons, CO, H_2	CH_4	N	T(OH)	5-10	1650	2340	1850-3300	A trend showing increase over the last 2 years has been identified
	C_2H_6	N	T(OH)	0.3	0.8	0.8	0.8-1.2	Predominantly of auto exhaust origin
	C_2H_2	A	T(OH)	0.3	0.06	0.1	0.06-0.16	No trend has been identified to date
	C_3H_8	N,	T(OH)	0.03	0.05	0.05	0.05-0.1	No trend has been identified to date
	CO	N,A	T(OH)	0.3	90	115	90-160	No trend has been identified to date
	H_2	N,A	T(SL,OH)	2	560	760	560-1140	
Ozone	O_3 (Tropospheric)	N	T(UV, SL,O)	0.1-0.3	F(Z)‡	12.5%		A small trend appears to exist but data are insufficient
Aldehydes	HCHO	N	T(OH,UV)	0.001	0.2	0.2		Secondary products of hydrocarbon oxidation
	CH_3CHO	N	T(OH,UV)	0.001	0.02	0.02		1980 concentration estimated from theory

*N, natural; A, anthropogenic; O, oceanic; S, stratosphere; UV, ultraviolet photolysis; T, troposphere; OH, hydroxyl radical removal; I, ionospheric and extreme UV and electron capture removal; SL, soil sink.

†These concentrations are integrated averages; for chemicals with lifetimes of 10 years or less, significant latitudinal gradients can be expected in the troposphere; for chemicals with extremely short lifetimes (0.001-0.3 years) vertical gradients may also be encountered.

‡Varies from 25 ppbv at the surface to about 70 ppbv at 9 km. The concentration was increased uniformly by the same percentage from the surface to 9 km.

Table 5. Net primary productivities (NPP) per given areas, total areas (in 1980), total NPP and actual biomass per ecosystem. The model calculated changes since 1780 are presented in brackets. (source: Ajtay, G.L. et al., Terrestrial primary production and phytomass. In: Bolin, B. et al. (eds), The Global Carbon Cycle, Scope Report No. 13, Wiley, New York, pp 129-187, 1979).

	(NPP) $gC.m^{-2}.yr^{-1}$	area 10^{12} m^2	NPP GtC yr^{-1}	biomass GtC
tropical forest	720	36.1 (- 8%)	27.8	324.7 (-18%)
temperate forest	510	17.0 (- 6%)	8.7	186.8 (-11%)
grassland	570	18.8 (+25%)	10.7	15.1 (+19%)
agricultural land	430	17.4 (+34%)	7.5	3.0 (+27%)
human area	100	2.0 (+1900%)	0.2	1.4 (+1200%)
tundra and semi-desert	70	29.7 (- 4%)	2.1	13.3 (+ 1%)
total		121.1	57.0	544.3

Table 6. Carbon emissions(in GtC) from the combustion of fossil and fuels (source: Group Scenario).

NEXT WAVE

	oil	commercial fuels coal	gas	total	total + NCE*
1983	2.52	2.36	0.77	5.65	6.28
1985	2.61	2.56	0.83	6.00	
1990	2.61	2.83	0.89	6.33	
1995	2.61	3.14	0.97	6.72	
2000	2.70	3.62	1.07	7.39	
2005	2.84	4.23	1.16	8.23	9.39

DIVIDED WORLD

	oil	commercial fuels coal	gas	total	total + NCE
1983	2.52	2.36	0.77	5.65	6.28
1985	2.59	2.50	0.81	5.90	
1990	2.70	2.66	0.87	6.23	
1995	2.81	2.95	0.92	6.68	
2000	2.88	3.28	0.98	7.14	
2005	3.03	3.66	1.01	7.70	8.87

* Non-Commercial Energy (biomass)

Table 7. Shell Group interest in fossil fuels in 1984 (source: 1985 information Handbook)

fuel	world production	Group interest	%
oil (million bbl/d)	58.2	4.5	7.7
gas (milliard m^3/yr)	1565	56	3.6
coal (million t/yr)	4147	32	0.8

Table 8. Contribution to global CO2 emissions from fuels sold by the Shell Group in 1984 (source: Shell Coal)

	carbon emissions (gigatonnes of carbon)	
fuel	total world	Group share
oil	2.56 (40%)	0.20 (3.1%)
gas	0.80 (12%)	0.03 (0.5%)
coal	2.46 (38%)	0.02 (0.4%)
NCE*	0.63 (10%)	0 (0.0%)
total	6.45 (100%)	0.25 (4%)

* NCE = Non-Commercial Energy (biomass)

APPENDIX 1

The CO_2/carbonate system in the ocean

The majority of carbon present in the ocean is in the form of dissolved inorganic carbon, i.e. 89% as bicarbonate ion (HCO_3^-), 10% as carbonate ion (CO_3^{--}) and 1% as dissolved CO_2. The thermodynamic equilibrium of all forms of inorganic carbon in the atmosphere and the oceans is determined by the following reactions:

$$CO_2 \text{ (atmosphere)} \rightleftharpoons CO_2 \text{ (dissolved)} \qquad (1)$$

$$CO_2 \text{ (dissolved)} + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \qquad (2)$$

$$HCO_3^- \rightleftharpoons CO_3^{--} + H^+ \qquad (3)$$

$$H_3BO_3 \rightleftharpoons H_2BO_3^- + H^+ \qquad (4)$$

$$H_2O \rightleftharpoons OH^- + H^+ \qquad (5)$$

In water carbonic acid largely dissociates, while only about 10% of bicarbonate dissociates. The chemical equilibria exert a buffering action on the uptake of additional CO_2 by the ocean. The equilibrium constants of the above reactions are:

$$H = p\,CO_2 / [CO_2] \qquad (6)$$

$$K_1 = [HCO_3^-]\,[H^+] / [CO_2] \qquad (7)$$

$$K_2 = [CO_3^{--}]\,[H^+] / [HCO_3^-] \qquad (8)$$

where
- [ ] = concentrations in water
- H = Henry's law constant
- pCO_2 = equilibrium partial pressure in the gaseous phase

The constant H is dependent on the temperature and K depends on temperature and salinity.

The concentration of total inorganic dissolved carbon is:

$$C = [CO_2] + [HCO_3^-] + [CO_3^{--}] \qquad (9)$$

and the alkalinity is defined as:

$$A = [HCO_3^-] + 2[CO_3^{--}] + [H_2BO_3^-] + [OH^-] - [H^+] \qquad (10)$$

The alkalinity arises from the dissolution of minerals in seawater, principally calcium carbonate. The alkalinity is defined as the amount of acid required to titrate 1 kg of seawater to a constant pH value, corresponding to conversion of bicarbonate and carbonate ions to carbonic acid.

An increasing concentration of CO_2 in seawater shifts equilibrium (2) to the right and by an increasing $[H^+]$ equilibrium (3) to the left. Thus, the principal effect is to consume carbonate ion:

$$\Delta H_2CO_3 + \Delta CO_3^{--} \longrightarrow 2\Delta HCO_3^- \qquad (11)$$

Δ: deviation from stationary state
The CO_2 added to the ocean (i.e. $\Delta\Sigma C$) is therefore:

$$\Delta \Sigma C = -\Delta[CO_3^{--}] \qquad (12)$$

As the concentration of bicarbonate is already very high, a change as a consequence of (11) is negligibly small and the relative changes in $[H_2CO_3]$ and $[CO_3^{--}]$ are practically of the same order:

$$\frac{\Delta[H_2CO_3]}{[H_2CO_3]} = -\frac{\Delta[CO_3^{--}]}{[CO_3^{--}]} \qquad (13)$$

Equations (12) and (13) can be transformed to:

$$\frac{\Delta[H_2CO_3]}{[H_2CO_3]} = \frac{\Delta\Sigma C}{[CO_3^{--}]} = \frac{\Sigma C}{[CO_3^{--}]} \times \frac{\Delta\Sigma C}{\Sigma C} \qquad (14)$$

As already mentioned above $[CO_3^{--}]$ is about 10% of the ΣC, so that the factor $\Sigma C/[CO_3^{--}]$ is about 10. As there is a simple relationship between the atmospheric CO_2 and the oceanic carbon concentration (1, 6), any change may be presented by:

$$\frac{\Delta pCO_2}{pCO_2} = \xi \frac{\Delta\Sigma C}{\Sigma C} \qquad (15)$$

This yields the so-called evasion factor:

$$\xi = \frac{\Delta pCO_2/pCO_2}{\Delta\Sigma C/\Sigma C} \qquad (16)$$

In case pCO_2 is explicitely identified to p_s (CO_2 partial pressure in the ocean surface layer), ξ is the evasion factor or the Revelle factor R, i.e. the "buffer factor". The factor varies with temperature and has a numerical value of about 10. In essence a 10% change in pCO_2 produces only a 1% change in CO_2.

If the CO_2content of the atmosphere and therefore of the surface ocean increases, $[CO_3^{--}]$ decreases and the value of ξ rises (see also Fig. 7). The resistance to change subsequently increases, the ocean absorbs proportionally less CO_2, and the airborne fraction rises. This complex

system is sensitive to the alkalinity / total CO_2 ratio, and hence pH. Adding CO_2 gas to seawater (11) does not change the alkalinity since charge balance is not altered (10); the dissolution or precipitation of $CaCO_3$, however, does.
The principal forms of $CaCO_3$ in the ocean are calcite and aragonite, which are secreted by calcareous organisms to form their shells. Surface seawater is supersaturated with respect to both calcite and aragonite. The solubility of $CaCO_3$ increases with increasing pressure, decreasing temperature and increasing pH; thus, the deep ocean is undersaturated and dissolution of $CaCO_3$ occurs there.

If CO_2 is added to the surface ocean, the pH decreases and the tendency for $CaCO_3$ dissolution increases. If this occurs, both the alkalinity (10) and the total CO_2 (9) increase. Although this process generates an increase in total CO_2, the net effect of the alkalinity increase would be to enhance the ocean's capacity for CO_2 uptake by keeping the buffer factor constant and providing CO_3^{--}-ions (16).

Recent reports on the greenhouse effect

What are some of the differences between the EPA and NRC studies?

Two reports published in late 1983 reach strikingly different conclusions about the greenhouse effect. A report prepared by a committee under the auspices of the National Research Council (NRC) subscribes to the view that uncertainties in our knowledge of the greenhouse effect are so great that we should take no action now except to study the problem more intensively. An EPA report that was released almost simultaneously concludes that even though a significant warming is likely if we continue on our present path, there is no feasible way to change this path enough to avert the warming by more than a few years. In brief, this view holds that we face almost certain unprecedented changes in the global climate but that we can do nothing but try to adapt to these changes. It is instructive to compare these peer-reviewed studies in terms of their analysis of energy use and resulting CO_2 emissions to ascertain why they arrive at such widely divergent conclusions.

Major findings

The EPA study predicts that CO_2 levels will reach 590 ppm, or twice preindustrial levels, by 2060. Increases in CO_2 and other greenhouse gases would most likely cause a 2 °C warming by 2040 and a 5 °C increase by 2100. Such temperature changes, the report states, "would represent a dramatic departure from historical trends" and "are likely to be accompanied by dramatic changes in precipitation and storm patterns and a rise in global average sea level," thereby causing major geographical shifts in agriculturally productive regions and disrupting established economic systems.

The EPA report examines various strategies to lessen the greenhouse effect. Of these, it concludes that only a worldwide ban on coal combustion instituted in the year 2000 or a ban on coal and shale oil use begun in the same year would have a substantial effect on the temperature increase in the year 2100. A total ban on coal would reduce the temperature increase

from 5 °C to 3.5 °C, whereas a total ban on coal and shale oil would reduce the increase from 5 °C to 2.5 °C. However, even if coal were phased out by 2000, the report predicts that the 2 °C warming would be delayed only about 15 years until 2055.

A worldwide tax of 100% on fossil fuels instituted in the year 2000 would be less effective, according to the report, reducing the warming by less than 1 °C in 2100; taxes up to 300% are predicted to delay the 2 °C warming only about five years beyond 2040. Even the alternative energy futures and changes in energy demand analyzed in the report cause a rather minor change, five years or less, in the date of a 2 °C warming. Because a ban on coal is neither economically nor politically feasible and because no other strategies seem to effectively mitigate the global warming, the report urges that individual countries study ways to adapt to rising temperatures.

The NRC report predicts that if no corrective measures are taken, CO_2 levels will most likely double at about the same time as is forecast in the EPA study, during the third quarter of the 21st century. A global temperature change of 1.5 °C to 4.5 °C is expected from this doubling, with values in the lower half of the range more probable. The NRC report differs from the EPA study in that it is far less pessimistic about the effectiveness of strategies that might be used to reduce CO_2 emissions. Substantial taxes on fossil fuel use are seen to have a strong effect on CO_2 emissions and to be "the most predictable in their emission-reducing impact." The report states that steps to change current energy use patterns away from fossil fuels may be necessary at some time in the future, implying that such steps could be effective, and recommends that research into nonfossil energy sources be stimulated. However, it does not recommend that strong steps to limit the burning of fossil fuel be taken in the immediate future, primarily because our knowledge of the CO_2 issue is fraught with uncertainties.

Different analytical techniques

One of the major reasons the EPA report stresses adaptation to what it perceives as inevitable changes and the NRC report stresses uncertainties in our knowledge of the greenhouse effect is that the reports employ quite different analytical techniques to derive their estimates of future fossil fuel use and the resulting future CO_2 emissions. In this area, although not in the entire report, EPA employs a deterministic approach, whereas NRC uses a probabilistic technique which focuses on how the accumulated uncertainties from each segment of its analysis affect the overall conclusions.

The NRC report takes two approaches to projecting future CO_2 emissions, both of which emphasize uncertainties. In one approach, nearly all previous long-range global energy studies are reviewed and the range of projections is used as a guide to the uncertainty inherent in projections of CO_2 emissions.

In the second approach, called "probabilistic scenario analysis," future emissions are estimated after key parameters are assigned a range of values. An attempt is made to estimate the range of current uncertainty as realistically as possible. The conclusion of this approach is that "CO_2 emissions will grow at about 1.6% annually

to 2025, then slow their growth to slightly under 1% annually after 2025." NRC states that its estimates are lower than those in many earlier studies for two major reasons: "First, the expected growth of the global economy is now thought to be slower than had earlier been generally assumed." Second, NRC includes in the analysis incentives to substitute other energy sources for fossil fuels as the prices for fossil fuels rise. Most other studies have downplayed the potential importance of this effect.

Both of NRC's approaches produced not a single value but a range of values for future CO_2 emissions, with higher probabilities assigned to some values than to others. In neither approach was an effort made to resolve uncertainties; rather, both approaches recognize that projections of the future become more and more uncertain as the time horizon expands.

Inevitable results

The EPA report also considers uncertainties in some sections, but in the core of the report, the analysis of future CO_2 emissions, it ignores them. The study adopts a set of economic assumptions to which no ranges of uncertainty are attached, and from these and the use of a global energy model derives what is called a reference mid-range baseline projection or scenario. Various policies intended to slow or limit the rate of CO_2 rise are then tested against this projection. Because the policies are tested against no other projections, the assumptions embedded in this mid-range projection are critical in determining the results of the policy analysis.

If the main elements of EPA's energy analysis are examined, it can be seen that EPA's conclusions follow almost inevitably from its assumptions. First, the agency assumes a rate of economic growth that would be considered high by a number of analysts. Gross world product is projected to increase from 6.06 trillion U.S dollars in 1975 to 184.87 trillion dollars in 2100, in constant 1975 dollars (a factor of 30 increase). The average annual rates of increase over the 125-year period range from about 2.8% per year for the developed regions to over 3% (3.8% after 2050) for the less developed nations. During this same time period, per capita gross national product (GNP) in African countries, for example, grows from an average of $375 per year to $14,000 per year in constant 1975 dollars.

The total energy demand is tied directly to the GNP by what are called income elasticities of demand. These are set at greater than or equal to one over the entire world to the year 2100. This means that as incomes go up, energy use goes up proportionately or greater than proportionately, except as it is affected by prices and enhanced energy efficiency.

The analysis is set up in such a way that no new technology such as solar or fusion becomes competitive with either coal or nuclear as a source of electric power to the year 2100. Solar and biomass both remain minor energy sources. Therefore, except for nuclear power, no economical substitute for fossil fuel emerges over the next 120 years. In contrast, the *EPRI Journal* concluded recently that for just one emerging energy technology, photovoltaics, "three approaches now have a better-than-even chance of meeting the cost and efficiency thresholds needed for bulk power generation."

Further, the EPA report assumes fixed price elasticities for fossil fuel demand that are independent of fuel cost. Thus, the economic attractiveness of increasing the efficiency of energy use or substituting other energy forms is assumed to be independent of fossil fuel prices. This assumption becomes particularly important as the rapidly increasing use of fuels exhausts the conventional oil and natural gas supplies and greater reliance on synthetic fuels from coal and on unconventional gas and oil is required. Many energy analysts believe that these costly forms of fossil fuel may not be economically competitive with other energy options in a number of situations.

A final assumption of the EPA study is that other greenhouse gases such as nitrous oxide, methane, and chlorofluorocarbons will have a warming effect approximately equal to that of CO_2. A large uncertainty is associated with this assumption, but it is used nevertheless in evaluating the effectiveness of various policies such as taxes or bans on various fossil fuels. It assumes that the warming from other greenhouse gases will mitigate the effect of lowering CO_2 emissions. For example, a 30% decrease in emissions produces only a 15% decrease in the expected warming.

Because none of these assumptions is changed in testing the various policies, none but the most stringent and therefore highly infeasible—such as a total ban on coal by the year 2000—substantially reduces CO_2 emissions and the resulting warming. Worldwide taxes of up to 100% on fossil fuels reduce emissions 10–42% in 2100, but the maximum estimated temperature reduction is only 0.7 °C.

Other projections

In the EPA report, a number of other energy scenarios are investigated, but all of them are variants of the mid-range scenario and none of them are used as baselines from which to assess the effects of different policies. The other scenarios are called high renewable, high nuclear, high electric, low demand, and high fossil. These all use the same growth forecast for GNP as is employed in the mid-range scenario. The low-demand scenario is the only one that projects a significant change in energy demand—24% less in 2050—and comparable reductions in CO_2 emissions.

The EPA study includes one scenario in which the growth rate in GNP is lowered somewhat, but it is decreased only after 2050 and only for the less developed regions, where it is reduced from 3.8% to 2.8% per year. The scenario projects a temperature rise in 2100 that is only 0.2 °C lower than it is in the mid-range scenario. From this analysis, EPA concludes in the executive summary that reduced economic growth causes only "minor [i.e., five years or less] changes in the date of a 2 °C warming."

The energy model used by EPA is not intrinsically inaccurate or unrealistic. But, the fact that only one run of the model is used to assess the implications of different policies and that this run involves assumptions to which no range of uncertainty is assigned introduces a certain inevitability to the conclusions. The NRC report describes this model as "the only carefully documented, long-run global energy model operating in the United States," but says that its size and complexity make "identification of critical parameters or assumptions a formidable task." Unfortunately, the EPA report does not even explain the possible importance of these critical assumptions to the conclusions it draws, nor does it analytically test the sensitivity of these conclusions to other sets of assumptions made by credible energy analysts and economists.

The EPA study is interesting because it shows that policies which at first glance appear useful may not be quick and easy answers to the greenhouse problem. It is misleading if it gives the impression that its projections are the only possible or probable ones or that all policies that might be instituted to mitigate the greenhouse effect are doomed to failure.

—Bette Hileman

APPENDIX 3

Current (1986) legislation and policies

General

Air pollution control today is only to a limited extent a local issue as it has become a regional and national matter in most countries. For some countries the main aspect of air pollution is only an international one. This holds particularly for the issue of carbon dioxide/climatic change. National governments are, of course, unlikely to agree as to the appropriate response to the CO2 problem, if they do not share similar views regarding the severity and the causes. Therefore, international forums are used as the appropriate environment for the universe of nations to discuss and debate such national and global concerns. All available knowledge can be registered there and research can be coordinated and stimulated.

It is not surprising that many countries involved in trans-boundary air pollution problems, also seriously fear socio-economic and climatic consequences of increasing CO2 concentrations. Although currently no legislation exists with regard to the CO2 problem, some of these countries are developing environmental policies at a national level. The USA and The Netherlands are here taken as examples because of their activities and initiatives in this field.

United Nations Environment Programme (UNEP)

The issue of carbon dioxide and climatic change has been on the UNEP agenda for many years. From a relatively unimportant subject it developed into a recurrent issue and recently clear links were shown to exist with issues such as deforestation and hazards to the ozone layer posed by chlorofluorocarbons (CFC's).

The following is a short historical overview of the main actions and recommendations related to the greenhouse effect.

During its seventh session in May 1979 the Governing Council of UNEP requested the Executive Director to bring to the attention of the World Meteorological Organisation (WMO) the willingness of UNEP to collaborate with WMO and other organisations concerned with the implementation of the climate impact studies component of the World Climate Programme. This offer was accepted by WMO. Following recommendations by the Scientific Advisory Committee of the World Climate Impact Studies Programme (WCISP), the Governing Council, in its ninth session in May 1981, called upon the Executive Director to proceed with implementation of the WCISP in collaboration with participating international organisations (i.e. WMO and the International Council of Scientific Unions).

During the tenth anniversary of the UN conference on the Human Environment in May 1982 the Governing Council defined the trends, problems and priorities for action which should receive attention by the UN system. With respect to the atmosphere the following items were identified. These include the continuing increase of CO2, other trace gases and particulates

in the atmosphere and possible effects of human activities on weather and climate.
The following actions were given priority:
- integrated monitoring of atmospheric pollutants and their effects
- development and promotion of appropriate global, regional and national programmes
- understanding of factors affecting climate, including ocean-atmosphere interaction

The Council requested the Executive Director to consider the appropriate timing for an assessment of the potential socio-economic impacts of increased CO_2 concentrations in the atmosphere and for the establishment of a committee to coordinate related research and information exchange. This in the light of the progress made by WMO and ICSU, in cooperation with the Food and Agriculture Organisation (FAO) of the United Nations and the United Nations Educational, Scientific and Cultural Organisation (UNESCO).

At the Ministerial Conference in June 1982 in Stockholm the UNEP Executive Director summarised UNEP's ten year review of the State of the World with respect to CO_2 as follows:
- Concentrations of CO_2 are slowly and steadily increasing, chiefly as a result of the increasing use of fossil fuels and forest clearing.
- A world climate programme has been initiated by WMO with UNEP's participation. UNEP has special responsibilities for the assessment of the impacts of climatic changes.
- No systematic attempt has yet been made to address the problem of managing the emissions of CO_2, most likely because of the long-term effect of their increase.
- It looks as if any initiative aimed at managing the CO_2 problem will not be taken in the near future and perhaps taken too late.

At the eleventh session of the Governing Council in May 1983 many delegations noted the importance of the increase in atmospheric CO_2, and several felt that the subjects of rational energy use and of new and renewable energy sources should be considered within the context of the CO_2 climate issue.

CO_2 related excerpts from the reports presented at the twelfth session of the Governing Council in May 1984 are given in Appendix 4.

European Community (EC)

In December 1979 the Council adopted the proposal for a five-year (1980-1984) indirect-action programme on climatology (1). The main objectives were to contribute to a better understanding of climatic processes and variations, and to assess the potential impact of climatic variations on basic resources and the effect of human activities on climatic variations.
This programme fitted in with the World Meteorological Organisation's World Climate Programme and included the following research areas:

a) understanding climate by reconstruction of past climates,
b) development and improvement of climate modelling, and
c) man-climate interaction studies with special emphasis on the accumulation of CO_2 and the effects of release of energy.

In 1980 the Commission submitted a proposal for a Council Decision adopting a sectorial research and development programme (indirect action) 1981-1985 (2). Sub-programme II on climatology outlined two research areas, i.e. understanding climate and man-climate interactions. The main objectives of this programme were to establish a scientific basis for the implementation of the Community's environmental policy and to promote long-term basic research on important environmental problems.

The public and senior governmental scientists grew more and more concerned about the implications of the rising CO_2 content of the atmosphere with regard to agricultural and human settlement patterns in the long-term. In the beginning of 1985 this concern was considered sufficiently real to justify the introduction of studies into possible alternative energy strategies.

In the research programme for 1986-1990 the Commission proposes in Sub-programme II on climatology and man-environment interaction to concentrate on the issues: understanding of man's influence on climate and prediction of the resulting impacts, with special emphasis on the increasing atmospheric CO_2 concentration.

At the end of October 1985 a comprehensive report on environmental constraints and their implications for EEC energy policy was presented at the plenary session of the Economic and Social Committee of the European Communications (ESC). The authors of this report argue that if the Community is to resolve the environmental problems resulting from energy production and usage, while at the same time ensuring adequate supplies of energy for the fast-growing world population, it must adopt a strategic approach based on a common policy for energy and the environment. The most important task will be to keep environmental pollution (including CO_2) from the production, conversion and usage of energy within acceptable limits at acceptable costs. The ESC unanimously decided to forward this report to the European Commission and the EEC's Council of Ministers (3).

1. OJ C247 of 18/10/1978, Bull. EC 12-1979, points 2.1.161
2. OJ C228 of 08/09/1980, p. 1
3. Europe Environment, November 12, 1985 - No. 243, V, 1-26

Organisation for Economic Cooperation and Development (OECD)

During its work on environmental policy, the OECD has established and adopted a series of principles with a view to their incorporation in national legislation and regulations concerning the protection of the environment and also in international agreements (e.g. 1,2,3).
Apart from recommendations with regard to long-range trans-boundary air pollution and reduction of environmental impacts from energy production and use, no special attention was paid to the CO_2 problem.

1. Coal and the environment (Recommendation adopted on 8th May, 1979 - C (79) 117)
2. Ministerial declaration on future policies for science and technology, PRESS/A (81) 14 (1981)
3. Reduction of environmental impacts from energy production and use (Recommendation adopted on 12th October, 1976 - C(76) 162)

USA

The Energy Security Act of 1980 (1), while focused on the development of synthetic fuels, also called for examination of some of the environmental consequences of their development. One such consequence perceived by the Congress was the build up of CO2 in the atmosphere, and the National Academy of Sciences (NAS) and the Office of Science and Technology Policy (OSTP) of the Executive Office of the President were requested to prepare an assessment of its implications. In response to a congressional mandate, the Carbon Dioxide Assessment Committee (CDAS) was formed and published a report (Changing Climate) in 1983.

As a result of a scientific conference in 1977 in Miami Beach, Florida and its recommendations, which were followed by the Department of Energy (DOE) and other federal agencies, including NSF, NOAA, NASA, EPA, USGS, and USDA, more than $ 110 million have been spent on CO2 research from 1978 to 1984.

1. Public Law 96-294, June 30, 1980; Title VII - Acid Precipitation Program and Carbon Dioxide Study; Subtitle B - Carbon Dioxide

The Netherlands

Concern about air pollution in general in The Netherlands has led to local, regional and national abatement policies in order to improve the air quality and the chance of survival of nature in remote areas. Over the last few years concern about the issue of carbon dioxide and climatic change has considerably increased and has resulted in a central policy laid down in the indicative multi-year air programme 1985-1989 (IMP-air (1)). There in certain facets were based primarily on advice received from the Health Council (2) and the Advisory Council for Research on Nature and Environment (3). The policy pursues the following principal strategies:

- The government will take the necessary measures to promote the awareness and knowledge of the CO2 problem and of trace gases which might influence the global climate. At the national level this will be elaborated by providing and publishing relevant information. However, it is recognised that the only effective way to tackle the problem is through international cooperation and exchange of information. As the CO2 problem receives attention in only a few countries and scientific organisations, the Dutch government will encourage international organisations such as UNEP, EOSD/IEA and EC, to expand their activities in this field.

- In order to narrow the uncertainties about future climatic changes and to define possible measures to reduce the impact, opportunities for scientific research will be provided in close cooperation with the EC

programme on climatology and the World Climate Programme.

- In line with the general air pollution abatement policy, measures to reduce emissions of CO_2 will be studied. Special attention will be paid to stimulation of energy conservation, alternative energy sources and reduction of fossil fuel usage.

1. IMP-air, Lower Chamber 18605, September 1984

2. Deeladvies inzake CO_2-problematiek, Gezondheidsraad, February 1983

3. Onderzoek in Nederland naar de gevolgen van de toename van CO_2 en andere sporengassen in de atmosfeer door menselijke activiteiten, RMNO, May 1984

UNITED NATIONS ENVIRONMENT PROGRAMME

LIST OF ENVIRONMENTALLY DANGEROUS CHEMICAL SUBSTANCES AND PROCESSES OF GLOBAL SIGNIFICANCE

REPORT OF THE EXECUTIVE DIRECTOR

OF UNEP

TO THE TWELFTH SESSION OF ITS GOVERNING COUNCIL

***

IRPTC - GENEVA

CONFIDENTIAL

CARBON DIOXIDE

Background

Carbon dioxide (CO_2) is a natural trace constituent of the earth's atmosphere. The present mean concentration of CO_2 is around 340 ppm by volume. CO_2 has a critical role in the global heat balance in that it is essentially transparent to the incoming solar radiation but absorbs the infra-red radiation emitted by the earth. This radiation trap causes a warming of the lower atmosphere which is known as the "greenhouse effect".

The global nature of the CO_2 problem results largely from the combustion of fossil fuels (oil, coal and natural gas) whose consumption has been increasing steadily since the beginning of the last century. The corresponding release of CO_2 has resulted in a significant build-up in the atmosphere, from an estimated concentration of less than 300 ppm in the middle of the nineteenth century to a present-day value of about 340 ppm. Reduced energy demand since the mid-1970s has caused a slight reduction in the annual increase in fossil fuel use and consequent CO_2 emissions.

Global impact

Several uncertainties surround the CO_2 issue and these place constraints on the assessment of CO_2's global impact. There are also deficiencies in our knowledge of the natural carbon cycle and its reaction to perturbation by human activities. For example, only about half of the CO_2 discharged from fossil fuels over the last two decades can be found in the atmosphere. It is commonly suggested that the oceans act as the main sink for this "missing" fossil fuel CO_2 although it is uncertain whether net transfer to the oceans can account for all the deficit. There is also uncertainty over the magnitude of CO_2 release arising from man's widescale and increasing forest clearance activities, with estimates ranging from insignificant to an amount comparable with fossil fuel CO_2, although most projections indicate that, in the long term, fossil fuel emissions will be an order of magnitude larger than biospheric emissions. If the latter is true, the fraction of man-made CO_2 which remains airborne is lower than present estimates indicate, suggesting that CO_2 increases will occur more slowly than currently predicted.

Uncertainties also surround the earth's future demand for fossil fuels and consequent CO_2 release. Some recent predictions estimate that atmospheric CO_2 concentrations may pass 600 ppm in the third quarter of the next century; this value represents a doubling of the pre-industrial concentration. It has also been forecast that the greatest increase in CO_2 release from fossil fuels will arise in the developing countries.

It is generally accepted that future increases in the atmospheric CO_2 level will cause a rise in the average global temperature. However, there is still debate over the magnitude of this warming. Calculations with three-dimensional, time-dependent models of the global atmospheric circulation indicate that a doubling of the CO_2 level will cause an average global warming of 1.5°C - 4.5°C with greatest increases predicted for the higher latitudes of the northern hemisphere.

These increases in temperature may lead to effects such as altered precipitation and evaporation regimes, which could affect agriculture and the distribution of food resources. Effects on the oceans may also be significant, as changes in wind circulation would affect ocean currents, causing the relocation of nutrient-rich areas leading to the redistribution of marine organisms and the consequent elimination of some commercial fisheries. Ocean warming and ice cap melting may raise the sea level by the order of one metre. One recent study considers a global rise of between 144 cm and 217 cm likely to occur by the year 2100.

Currently there is no evidence that there has been a CO_2-induced increase in the global temperature. The detection of such an effect is made difficult by the inherent variability in climate. In addition, predictions of the time when a global warming will be detectable are highly dependent on the assumed rate of heat exchange between different parts of the oceans.

Several approaches to control the CO_2 problem have been proposed. The "technical fixes" which involve the collection and disposal of CO_2 are not considered to be practical or economical. Alternative energy systems which do not emit CO_2 might be developed to reduce the reliance on fossil fuels although such actions are currently considered to be of limited effectiveness and prohibitively expensive. Energy conservation is considered to be an important means of reducing CO_2 emissions from fossil fuels.

\- - - - - - -

RECOMMENDATIONS

(a) Because replacement of fossil fuels by alternative energy sources is probably still not feasible economically and politically, priority should be given to work geared to the development of long-term energy options not based on combustion of fossil fuels;

(b) The size of reservoirs and fluxes in the biogeochemical cycle of carbon should be determined with greater accuracy;

(c) The modelling of CO_2-induced climate changes should be further refined to reflect, for example, interactions of the ocean-atmosphere interface in order to establish more accurately the size and extent of predicted effects;

(d) Research and development should give priority to better predictions of future fossil fuel use and corresponding CO_2 release to atmosphere;

(e) Updated assessments of the CO_2 climate issue should be undertaken jointly by a WMO/ICSU/UNEP CO_2 study group with an appropriately broad interdisciplinary membership. A second assessment of the role of CO_2 in climate variations and their impact should be made in 1985.

CONFIDENTIAL

UNEP REPORT NO. 2 (1984)

UNITED NATIONS
ENVIRONMENT PROGRAMME

LIST OF ENVIRONMENTALLY DANGEROUS CHEMICAL SUBSTANCES AND PROCESSES OF GLOBAL SIGNIFICANCE

SCIENTIFIC MONOGRAPHS

***

IRPTC - GENEVA

CARBON DIOXIDE

Background

Carbon dioxide (CO_2) is a natural constituent of the Earth's atmosphere. It makes up only about three-hundredths of one per cent of the atmosphere, yet plays a crucial role in the planet's heat balance. This is because CO_2 absorbs infra-red radiation emitted from the Earth's surface, producing a warming of the lower atmosphere. This radiation trap is known as the "greenhouse effect".

It is now established that there has been a significant increase in the atmospheric CO_2 concentration since the beginning of the industrial era. Estimates of the airborne CO_2 level in the mid 19th century are in the order of 260-280 ppm (NAS 1983). Regular monitoring measurements from around the world reveal that by 1958 the CO_2 concentration had increased to about 315 ppm, while in 1980 the value had risen further to about 338 ppm (Bacastow and Keeling, quoted in Smith, 1982).

The rise in the atmosphere CO_2 level largely results from the combustion of fossil fuels (oil, coal and natural gas) whose use has been increasing at a steady rate since the beginning of the 19th century. Numerous studies have reported that CO_2 discharges from fossil fuel production have increased at an annual rate of about 4.5 per cent, at least until 1973 (e.g., Rotty 1981). As a result of the oil crisis and subsequent economic recession, there has been a slowing down of this increase to about two per cent. Currently, about 5×10^9 tonnes of CO_2 ($\pm$ 10 per cent) are emitted annually from fossil fuel combustion.

The global carbon cycle

The significance of atmospheric CO_2 accumulation should be examined in the context of the global carbon cycle. Unfortunately, although the principal sources, sinks and transfer kinetics are well established (Bolin *et al*. 1979), there are still uncertainties in regard to several important details of the cycle. For example, a quantity, somewhat larger than half of the CO_2 released from fossil fuels over the last two decades, is found in the atmosphere, indicating the presence of a CO_2 sink as yet unaccounted for. It is commonly suggested that the oceans act as the main sink for this "missing" fossil fuel CO_2, although it is far from clear whether net transfer to the oceans can account for all the deficit. Uncertainty also exists in the magnitude of CO_2 release from changes in land use, particularly deforestation. Estimates of the CO_2 released from this source range from insignificant to an amount comparable with fossil fuel CO_2 (Rotty 1980; Woodwell, G.M. *et al*. 1983). If the latter is true, the fraction of man-made CO_2 which remains airborne, is lower than present estimates indicate, suggesting that CO_2 increases will occur slower than currently predicted.

Superimposed upon these deficiencies in our understanding of the carbon cycle is the uncertainty surrounding future energy demands and consequent CO_2 release. Until recently, most forecasts of future fossil use were based on the high growth rates of energy demand in the early 1970s (e.g. Rotty 1978). However, most study groups have now revised their predictions of energy demand downwards (Häfele *et al*. 1981; Rotty 1980). These later estimates of future CO_2 release can be used in conjunction with currently accepted models of the carbon cycle to produce forecasts of future atmospheric CO_2. The values obtained are dependent on the assumption employed, but several estimates indicate that by the year 2025 atmospheric CO_2 levels could have risen to 450 or even 600 ppm (Rotty 1980; Smith 1982). A more recent study has predicted that atmospheric CO_2 concentrations may pass 600 ppm by the third quarter of the next century. For the year 2000, the most likely concentration is 370 ppm (NAS 1983).

Global effect of increased atmospheric CO_2

It is generally accepted that future increases in atmospheric CO_2 levels will be accompanied by a rise in the average global temperature. There is, however, uncertainty in regard to both the magnitude of this warming and to when the increase will be detectable. Most studies of this subject have used climate models to stimulate the CO_2-induced warming of the Earth. Currently, the most popular types are the General Circulation Models (GCMs). These are complex, three-dimensional atmospheric models which are considered to stimulate average climate conditions well, but to be less accurate in predictions of regional climatic change (NAS 1979). The results of most recent GCM investigations indicate that a doubling of the atmospheric CO_2 concentration from 300 to 600 ppm, if maintained indefinitely, will produce an average global warming of between 1.5 and 4.5°C, although values in the lower half of this range are most probable (NAS 1983). It is forecast that the greatest increases will occur in the higher latitudes, especially in the Northern Hemisphere.

It is conceivable that the consensus obtained between recent GCM studies may be spurious and could result from the common methodology employed by such investigations. In this respect, it is of interest to note that an independent approach, using radiation balance measurements, obtained a value of <0.26°C for the increase in temperature due to a doubling of the CO_2 level (Idso 1980). This study has, however, been widely criticized for several reasons, particularly for ignoring the feedback mechanism whereby greater evaporation from the oceans would cause an increase in the moisture content of the atmosphere, which in turn results in an enhanced "greenhouse effect" (Schneider, Kellogg and Ramanathan 1980).

Results from several GCM investigations indicate that a CO_2-induced increase in global temperature should already be detectable (e.g. Madden and Ramanathan 1980). Currently, however, there is no generally accepted evidence that such an increase has taken place. The detection of such an effect or "signal" is made difficult by the "noise" arising from the inherent variability of climate. This problem is exacerbated because attempts to detect such an effect have relied on observations of a single variable such as mean summer temperatures at a particular latitude. It has, therefore, been proposed that physical as well as statistical evidence should be sought, such as the relationship between tropospheric and stratospheric temperatures (Madden and Ramanathan 1980). In addition, a critical examination of GCM studies (Schlesinger 1983) revealed that the predicted time when a CO_2-induced warming will be detectable is highly dependent on the assumed rate at which heat is exchanged between the oceanic mixed layer and the deeper ocean. This uncertainty needs to be reduced to allow better predictions of the time of first detection.

Regional impact of increased global temperature

An important finding from GCM studies is that regardless of the reason for an increase in global temperature, there are general similarities in the pattern of climatic change. The regional implications of a global warming may therefore be assessed by reference to the past as a guide for future patterns of climatic change. Pollen records from one of the four warm epochs during the last 2.5 million years have been used to reconstruct rainfall patterns for different parts of the world (Kellogg 1978). The findings obtained have been criticized as the records are often poorly dated. The recent past, for which instrumental records are available, is considered to be a more useful guide for establishing possible patterns of climatic change. One such study (Wigley, Jones and Kelly 1980) compared conditions in the five warmest years between 1925 and 1974 with the five coldest in the period, using data from the high northern latitudes, the region where CO_2-induced changes are predicted to be greatest. Temperature increases were obtained for most regions, with maximal warming in the continental interiors at high

latitudes. Estimation of the human and environmental consequences of such climatic changes can only be speculative and uncertain. Adverse effects in one part of the world may be compensated by a beneficial effect in another region (WCP 1981).

A warming of the globe will result in changes of wind strength and elevation over the oceans which may alter the location of areas of upwelling and cause shifts in the distribution of marine organisms and the consequent elimination of some commercial fisheries (Stewart 1980).

A global warming will also cause the thermal expansion of the oceans and the transfer of ice and snow from the land to the oceans, resulting in an increase in the sea level. It is not possible to predict the precise increase, but a recent study has forecast that a global warming of about 3 or 4°C over the next 100 years will cause an increase in the sea level of about one metre (NAS 1983). Another study predicts a global rise of sea level of between 144 cm (4.8 ft) and 217 cm (7 ft) by 2100 as most likely, although a global rise as low as 56 cm (1.9 ft) or as high as 345 cm (11 ft) cannot be ruled out (EPA 1983).

Control strategies

It is difficult to suggest specific actions to alleviate the CO_2 problem when so many uncertainties surround the issue. However, if there is a consensus that CO_2 accumulation requires control, then two broad strategies can be considered. The first involves the use of technological countermeasures to collect CO_2 from the air, or from the flue gases of power stations. A detailed assessment of such an approach (Albanese and Steinberg 1980) concluded that the various techniques available were not practical because of the large energy costs involved. It must also be borne in mind that the expertise for such techniques is located in the developed countries, yet future energy growth is expected to be greatest in the developing nations.

The second approach to this problem is a preventive strategy, to reduce CO_2 release from energy production. A policy of drastically restricting the consumption of fossil fuels is not considered to be practical at the present time, as other forms of energy could not meet the increased demand (Smith 1982). Nevertheless, an expert group on energy demand and supply recommended a "low-climate-risk energy policy" requiring the development of alternative energy systems which do not release CO_2 to the atmosphere (Bach, Pankrath and Williams 1980). The adoption of alternative energy systems would, however, entail additional risks whose nature and magnitude are not always well known. It would, therefore, be beneficial to conserve energy from conventional sources as a means to reduce CO_2 release. Studies from several countries reveal that large savings in energy wastage can, or already have been, made (Kellogg and Schware 1981).

It must be stressed that any effort to minimize the impact of atmospheric CO_2 accumulation should involve the improvement of world agriculture. In this way, it will be possible to reduce the vulnerability of agricultural systems to climatic change. This is a dual-benefit approach, as the climate will fluctuate whether there is CO_2 accumulation or not. An increase in agricultural resilience would result from the protection of soils by improved land management practices and the development of cultivars which are adapted to a wide range of climatic conditions (Schneider and Bach 1980).

APPENDIX 5

International organisations and information centers

Scientific Committee on Problems of the Environment (SCOPE)

SCOPE is one of the 10 scientific committees established by the International Council of Scientific Unions (ICSU). Currently, representatives of 34 member countries and 15 Unions and Scientific Committees participate in the work of SCOPE.

The mandate of SCOPE is to assemble, review, and assess the information available on man-made environmental changes and the effects of these changes on man; to assess and evaluate the methodologies of measurement of environmental parameters; to provide an intelligence service on current research; and by the recruitment of the best available scientific information and constructive thinking to establish itself as a corpus of informed advice for the benefit of centres of fundamental research and of organisations and agencies operationally engaged in studies of the environment.

SCOPE's project on Biogeochemical Cycles has provided a forum to assess existing knowledge on the carbon cycle and to define fields of ignorance. The results and recommendations of a six day workshop (held in 1977 at Ratzeburg, FRG and financially supported by SCOPE, UNEP, the Research Council, the University of Hamburg and Shell), have been laid down in SCOPE Report 13, i.e. The Global Carbon Cycle (1979).

Another relevant publication in this field is SCOPE Report 16, i.e. Carbon Cycle Modelling (1981).

The World Climate Conference of 1979, in Geneva (organised by WMO, UNEP and SCOPE-ICSU) resulted in a World Climate Programme (WCP). The WCP includes a study of impact analysis of a changing climate. A team of 26 authors from 16 countries, led by Robert W. Kates, is preparing a SCOPE report, which will be a prescriptive document for the design of climatic impact assessments.

SCOPE Secretariat
51 Boulevard de Montmorency
75016 Paris
France

World Meteorological Organisation (WMO)

Since a rapid shift in the 1970's from traditional meteorology towards a climatic focus, WMO concentrates on climatic themes. The climatic system is seen as an entire whole, involving interaction between atmosphere, ocean, biota, soils, rocks, ice and human society. WMO's conversion culminated in the World Climate Conference of 1979, in Geneva (organised by WMO, UNEP and SCOPE-ICSU), which concentrated attention on the links between society and variable climate.

Out of this conference came a World Climate Programme, with four component programmes:

- The World Climate Application Programme (WCAP) "to assist societies to improve their capabilities to carry out various activities and to obtain maximum economic and social benefit under different climatic conditions, while maintaining environmental integrity".
- The World Climate Research Programme (WCRP) "to what extent of man's influence on climate".
- The World Climate Impact Studies Programme (WCIP) "the basic studies should aim at an integration of climate, ecological and socio-economic factors which enter into the complex problems facing society, in particular those relating to food, water and energy".
- The World Climate Data Programme (WCDP) "to ensure availability of reliable climate data which are accessible and exchangeable in an acceptable form and time, as required in climate research, applications and impact studies".

WMO
P.O. Box 5
Geneva 20
Switzerland

International Carbon Unit (ICU)

In cooperation with SCOPE/UNEP an International Carbon Unit has been established at the University of Hamburg, aimed at the collection of information on the carbon cycle. The ICU is headed by Prof. Dr. Egon T. Degens. Sub-units are located at the Vrije Universiteit of Brussels (cartography), the University of Stockholm (atmospheric systems and models), the University of Essen (socio-economic aspects) and in Woods Hole Mass. (land biota).

Prof. Dr. Egon T. Degens
Geologisch-Paläontologisches Institut
Universität Hamburg
Bunderstrasse 55
200 Hamburg 13
FRG

Global Environmental Research Organisation (GERO)

Italian and American scientists agreed at the end of October 1985 to set up a new international research institute (GERO) on an island in the Venice lagoon. It will be the first to be dedicated to global, interdisciplinary studies of the environment. Study themes will cover energy flow through the biosphere, including climatic linkages between atmosphere and ocean, biogeochemical cycles, ranging from acid rain, and greenhouse effect to oceanic sediments.

Carbon Dioxide Information Center (CDIC)

The CDIC supports the US carbon dioxide research program and cooperates in information exchange with the international scientific community

addressing global atmospheric CO2 problems. CDIC is sponsored by the Department of Energy's (DOE) Carbon Dioxide Research Division and is administered by the Information Division at Oak Ridge National Laboratory.

- CDIC maintains a Bibliographic Information System containing over 7000 keyworded references.
- it maintains an International Directory of approximately 1700 CO2 researchers.
- it publishes CDIC Communications, a biannual newsletter that reports on many aspects of CO2-related research projects, events, meetings, and publications.

CDIC
Oak Ridge National Laboratory
P.O. Box x
Oak Ridge, Tennessee, U.S.

Canada

Environment Canada publishes a quarterly newsletter, CO2 Climate Report, that will stimulate as well as update CO2 information within the Canadian research community.

Atmospheric Environment Service
4904 Dufferin Street
Downsview, Ontario M3H 5T4, Canada

APPENDIX 6

Institutes involved in CO2/climate/greenhouse effect research

A. Use of theoretical climate system models

British Meteorological Office
Bracknell, U.K.
(B.J. Mason; J. Gilchrist)

Department of Atmoshperic Sciences
Oregon State University, Corvallis, Oregon, U.S.
(W.L. Gates)

Department of Meteorology
University of Stockholm, Stockholm, Sweden
(B. Bolin)

Department of Meteorology, U.C.L.A.
Los Angeles, California, U.S.
(Y. Mintz; A. Arakowa)

Geophysical Fluid Dynamics Laboratory
NOAA, Princetown, New Jersey, U.S.
(S. Manabe; K. Bryan; R.T. Wetherald)

Goddard Space Flight Center
Greenbelt, Maryland, U.S.
(M. Hallion; Y. Mintz)

National Center for Atmospheric Research
Boulder, Colorado, U.S.
(W.M. Washington; R.E. Dickinson; W.W. Kellogg)

B. Reconstruction of real climatic change of the past

1. Instrumental record and paleoclimatology

Climate Research Unit
University of East Anglia, Norwich, U.K.
(T.M.L. Wigley; H.H. Lamb)

Institute for Environmental Studies
University of Wisconsin, Madison, Wisconsin, U.S.
(J.W. Kutzbach; R.A. Bryson)

Meteorological Institute
University of Bonn, Bonn, F.R.G.
(H. Flohn; S. Nicholson)

2. Instrumental record

Climatic Diagnostic Center, NOAA
Suitland, Maryland, U.S.
(D. Gilman)

CSIRO, Melbourne, Australia
(B.W. Pittork, B. Tucker)

Department of Meteorology
M.I.T., Cambridge, Massachusetts, U.S.
(R. Newell)

Department of Meteorology
University of Stockholm, Stockholm, Sweden
(S-A. Odh; J. Heintzenberg)

Department of Meteorology
Colorado State University, Fort Collins, Colorado, U.S.
(E. Reiter)

Environmental Data Service and Air Resources Laboratory, NOAA
Silver Spring, Maryland, U.S.
(J.M. Mitchell; J.K. Angell; K. Korchover)

National Center for Atmospheric Research,
Boulder, Colorado, U.S.
(H. van Loon; R.L. Madden)

3. Paleoclimatology

Arctic and Alpine Institute
University of Colorado, Boulder, Colorado, U.S.
(J. Ives; J. Andrews; N. Nichols)

Brown University
Providence, Rhode Island, U.S.
(J. Imbrie)

Geologisch-Paläontologishes Institut
University of Hamburg, Hamburg, F.R.G.
(E.T. Degens)

Lamont Geological Observatory
Columbia University, Palisades, New York, U.S.
(G. Kukla)

C. Sources and sinks for CO2 in the biosphere

Department of Theoretical Production Ecology
Agricultural University, Wageningen, The Netherlands
(J. Goudriaan)

CSIRO, Canberra, Australia
(G. Pearman)

Duke University
(K.R. Kramer)

Lawrence Livermore Labs
California, U.S.
(G. Bingham)

Marine Biological Laboratory
Woods Hole Oceanographic Institute, Massachusetts, U.S.
(G.M. Woodwell)

NOAA Research Labs
Boulder, Colorado, U.S.
(B. Bean)

University of Nebraska, Lincoln
(S.B. Verma; N.J. Rosenberg)

D. Biomass production

University of Ghent, Belgium
(R. Lemeur)

University of Antwerp, Belgium
(I. Impens)

University of California, Berkely, California, U.S.
(M. Calvin)

U.S. Forest Service, Rhinelander, Wisconsin, U.S.
(D. Dawson)

E. Crop modeling related to CO2 and climate change

Crop Simulation Research Unit
Mississippi State College, Mississippi, U.S.
(D.N. Baker)

Department of Agricultural Engineering
Clemson University, South Carolina, U.S.
(J. Lambert)

Evapotranspiration Laboratory
Kansas State University, Manhattan, Kansas, U.S.
(E.T. Kanemasu)

Temple, Texas
(G. Arkin)

University of Florida
(K. Boote)

University of Kentucky, Lexington
(W. Duncan)

University of Nebraska, Lincoln
(J. Norman; G. Meyer)

University of Wisconsin, Madison
(G. Cottam)

U.S. Department of Agriculture (USDA)
Ithaca, New York, U.S.
(T. Sinclair)

USDA
Temple, Texas, U.S.
(J.T. Ritchie)

U.S. Water Conservation Laboratory
U.S. Department of Agriculture, Phoenix, Arizona, U.S.
(S.B. Idso)

F. Social and economic consequences of climate change

Arbeitsgruppe Umwelt, Gesellschaft, Energie
University of Essen, Essen, F.R.G.
(K. Meyer-Abich)

Kennedy School of Government
Harvard University
(T.C. Schelling)

APPENDIX 7

Relevant publications (reports and books)

Andersen, N.R.; Malahoff, A. (eds)
The Fate of Fossil Fuel in the Oceans
Plenum Press, NY, 1977

Bach, W.
Our Threatened Climate: Ways of Averting the CO2 Problem through Rational Energy Use
Kluwer Acad. Publ., Hingham, MA, 1984

Bach, W. (ed.)
Carbon Dioxide: Current Views and Developments in Energy/Climate Research
Kluwer Acad. Publ., Hingham, MA, 1983

Bach, W.; Pankrath, J.; Williams, J. (eds)
Interactions of Energy and Climate
Reidel, Dordrecht, The Netherlands, 1980

Barth, M.C.; Titus, J.G. (eds)
Greenhouse Effect and Sea Level Rise: A Challenge for this Generation
Van Nostrand Reinhold, Florence, KY, 1984

Berger, A.L.; Nocolis, C. (eds)
New Perspectives in Climate Modelling
Elsevier, Amsterdam, The Netherlands, 1984

Bolin, B.
Carbon Cycle Modelling
Scope Report 16, Wiley, NY, 1981

Bolin, B.; Degens, E.T.; Kempe, S.; Ketner, P. (eds)*
The Global Carbon Cycle
Scope Report 13, Wiley, NY, 1979

Carbon Dioxide Assessment Committee
Changing Climate
National Academy Press, Washington, DC, 1983

Clark, W.C. (ed.)
Carbon Dioxide Review: 1982
Oxford Univ. Press, NY, 1982

Cushing, D.H.
Climate and Fisheries
Academic Press, NY, 1983

Geophysics Study Committee (GSC)
Energy and Climate
National Academy Press, Washington, DC, 1977

Häfele, R.*
Energy in a Finite World. A Global Systems Analysis
Ballinger Publ. Co., Cambridge, MA, 1981

Hill, A.E.
Atmosphere - Ocean Dynamics
Academic Press, NY, 1982

Houghton, J.T. (ed.)
The Global Climate
Cambridge Univ. Press., NY, 1984

Idso, S.B.*
Carbon Dioxide: Friend or Foe?
IBR Press, Tempe, Arizona, 1982

Jäger, J.
Climate and Energy Systems: a Review of their Interactions
Wiley, NY, 1983

Kellogg, W.; Schware, R.
Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide
Aspen Institute, Boulder, CO, 1981

Lemon, E.R.
CO2 and plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide
West View Press, Boulder, CO, 1983

Liss, P.S.; Crane, A.J.*
Man-Made Carbon Dioxide and Climate Change: A Review of the Scientific Problems
GEO Books, Norwich, England, 1983

MacDonald, G.J. (ed.)
The Long-Term Impacts of Increasing Atmospheric Carbon Dioxide Levels
Ballinger, Cambridge, Mass, 1982

McBeath, J.H.; Juday, G.P.; Weller, G.; Murray, M. (eds)
The Potential Effects of Carbon Dioxide-Induced Climatic Changes in Alaska
Univ. of Alaska, School of Agriculture and Land Resources Management
Miscellaneous Publication 83-1, Fairbanks, AK, 1984

National Research Council (NRC)
Carbon Dioxide and Climate: a Scientific Assessment
National Academy Press, Washington, DC, 1979

National Research Council
Energy in Transition 1985-2010
Final Report of the Committee on Nuclear and Alternative Energy Systems (CONAES)
W.H. Freeman, San Fransisco, 1979

National Research Council
Carbon Dioxide and Climate: a Second Assessment
Report of the CO2/Climate Review Panel, J. Smagorinski, chairman
National Academic Press, Washington, DC, 1982

Oerlemans, J.; Van der Veen, C.J.
Ice Sheets and Climate
Kluwer Acad. Publ., Hingham, MA, 1984

Organisation for Economic Cooperation and Development / International Energy Aency Workshop on Carbon Dioxide Research and Assessment
Paris, OECD/IEA, 1981

Seidel, S.; Keyes, D.
Can we Delay a Greenhouse Warming?
U.S. EPA, Washington DC, 1983

Smith, I.M.
Carbon Dioxide from Coal Utilization
Technical Information Service, International Energy Agency, Paris, 1982

Smith, I.M.
Carbon Dioxide-Emission and Effects
Report No. ICTIS/TR18, IEA Coal Research, London, 1982

Sundquist, E.T.; Broecker, W.S. (eds)
The Garbon Cycle and Atmospheric CO2: Natural Variations Archean to Present
American Geophysical Union, Washington, DC, 1985

Tucker, G.B.
The CO2-Climate Connection
Australian Academy of Science, Canberra, 1981

UNEP
Meeting of the Scientific Advisory Committee of the World Climate Impact Studies Programme
Nairobi, 23-27 February, 1981

US-DOE
Carbon Dioxide Effects Research and Assessment Program
Series of Publications by the US Department of Energy, CONF-7904143, 1980

Van Loon, H. (ed.)
Climates of the Oceans. Vol. 15, World Survey of Climatology
Elsevier, Amsterdam, The Netherlands, 1984

WMO/ICSU/UNEP
On the assessment of the role of CO_2 on climate variation and their impact
(based on meeting of experts, Villach, Austria, November 1980)
World Meteorological Organization, Geneva, January, 1981

World Meteorological Organization (WMO)
World Climate Conference: extended summaries of papers and declarations
WMO, Geneva, 1979

* Books recommended for general reading.

APPENDIX 8

Visit to Climate Research Unit, 27.11.1985

Meeting with Dr. T.G. Wigley, Director.

The CRU made a study of the greenhouse effect for Shell in about 1981 on the basis of a grant for £10000. This was subsequently extended for the US DOE and was published by them in August 1984 (I was given a copy of the report).

I found Wigley very much had his feet on the ground and was at great pains to emphasise the uncertainties that still exist in this area and the time needed before which it will be possible to reach any very definite conclusions about the greenhouse effect. Having said that, he was prepared to stick his neck out and say that there has been a global warming over the last 100 years, that the 0.5 degrees (range 0.3-0.7) increase is a result of CO_2 build-up, that we will see a further 1-2 degree warming over the next 40 years and that the warming will be greater in higher latitudes and more in winter than in summer. Such a rise would be greater than any change in the last 1000 years - at the peak of the last ice age (18000 years ago) the global mean temperature was 4 degrees lower than at present.

The global mean sea level has risen by some 15cm over the last 100 years, one third due to expansion of sea water and one third due to the melting of land ice (the melting of sea ice has no effect on sea level). A 4 degree warming might result in the disappearance of all Atlantic sea ice in the summer months. By 2050, the range of uncertainty of the rise in global mean sea level is 20-120cm.

On a time scale of decades, the role of the oceans as a thermal buffer is as important as the atmosphere and we are not capable at present of modeling the ocean or its coupling with the atmosphere. It is possible that the negative feedback of this coupling could wipe out the forecast rise. The movement of the sea ice boundary and the deep water formation affect the atmosphere and European climate very sensitively to the extent that Europe saw a cooling from 1040 to 1970 while the global mean temperature was static or rising. It is very difficult to model the ice movement which is mostly responding to water movements from below.

While most people agree that the warming will be amplified at higher latitudes this has not been measured because it has been countered by the cooling in the N. Atlantic region.

By the turn of the century we will have a much better idea of what caused past changes - our monitoring of the upper atmosphere, the oceans and solar output will have improved immeasurably. For example, only since the late fifties have we had data that will allow the modeling of the atmospheric behaviour in three dimensions the data suggests that while the lower atmosphere is warming, the upper is cooling.

Wigley is very interested in the effects of trace gases. He believes that it is not realistic to make policy decisions aimed at reducing the effect of CO2 but that we might reasonably do so for the trace gases. On a one-dimensional (global averaging) basis, the overall effects of chlorofluorocarbons, nitrous oxide, methane and ozone are roughly the same as CO2. In a two dimensional model the effects might be slightly less but there is not enough data to be certain. This is another area where will be much better informed in the next 10-15 years.

Water vapour alone has a positive feedback but there is great uncertainty about the effect of clouds. These can be both positive and negative, trapping heat and reflecting incoming radiation. Further, the effects of the same types of clouds can be different at different latitudes. Next to the ocean, this is the biggest uncertainty. For example, we are only now beginning to model the physics of the passage of radiation through clouds.

The most difficult effect of a global warming to predict is that on rainfall. Dynamic climatology is, after all, a very new science! In high latitudes (60-70 degrees, for example), rainfall ought to increase just because of the raised temperature; we may, after all, be doubling the water vapour content. Monsoon rainfall ought to increase also as should the frequency of tropical storms which is again a temperature dependent phenomenon. It is much more difficult to say anything about the mid-latitude drying forecast by some modeling and even more so to make sensible comments on possible changes in equatorial regions.

M.H. Griffiths

28th November 1985.